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USE OF DOPPLER RADAR IN METEOROLOGICAL OBSERVATIONS

ROBERT L. SMITH AND DAVID W. HOLMES

U.S. Weather Bureau, Washington, D.C.

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ABSTRACT

The U.S. Weather Bureau has been experimenting with a radar operating on the Doppler principle to determine whether apparatus of this type would detect and uniquely identify tornadoes. The principles of Doppler radar as applied to meteorology and results of recent experiments with equipment of this type are discussed. Calculations of anomalous wind speeds of 206 m.p.h. in a funnel cloud and 94 m.p.h. in a dust devil are presented in detail. In addition, data have been gathered from squall lines and isolated thunderstorms. Recommendations are made for an optimum Doppler radar system for the detection of tornadoes.

1. INTRODUCTION

A number of techniques are being employed in an effort to detect tornadoes with radar. The best known of these is identification of "hook echoes". Although this has been rather successful in a few cases, there is urgent need for a unique instrument or technique that will identify tornadoes far more frequently than has been done with the conventional type weather search radar. Following the suggestion of Brantley [4], then of Cornell Aeronautical Laboratory, the U.S. Weather Bureau began, in the fall of 1956, an experimental program to determine the feasibility of using radar operating on the Doppler principle for detection of tornadoes.

Radar employing the Doppler principle measures the instantaneous speed of any moving object relative to the observing point. In contrast, conventional weather search radar presents a plan view of the direction and range of objects from the radar station. Pulse and continuous wave systems are, in principle, capable of approximately the same range performance per average power [6]. An unmodulated continuous-wave radar yields no range information because no reference is provided on the transmitted wave that can be timed from emission to reception. It should be noted that in a system such as this, the intensity of the echo is proportional to the range weighted integral of all target cross-sections along the beam.

The Weather Bureau obtained from the U.S. Navy a 3-cm. continuous-wave Doppler radar (fig. 1), had it

FIGURE 1.—The 3-cm. continuous-wave Doppler radar equipment trailer.

modified for meteorological use in 1957 and additionally modified in 1959. This continuous-wave (cw) radar operates on a frequency of 10,525 mc. sec.$^{-1}$. The major components of the equipment are the transmitter, receiver, and two 6-foot parabolic reflectors. The transmitter output is an unmodulated carrier which is fed into the directive transmitting antenna. The reflected signal is fed from the receiving antenna to the detector and the audio amplifier. The two parabolic reflectors, each with a beam width of 1.8°, are mounted side by side on a pedestal and rotate together. With this system, some of the transmitted energy leaks into the receiver. Thus the transmitted signal and the reflected signal are compared in the receiver. The difference between the frequencies of these two is converted to a receiver output audio tone whose pitch varies directly with the target speeds. The audio signals are recorded on magnetic tape and, at the same time, are fed into an ultrasonic frequency spectrum analyzer for immediate inspection. The tapes are used later for additional detailed analysis. The operating controls, recording and analyzing equipment are inside the body of the trailer. In addition, a radar repeater is connected to a nearby conventional weather search radar so that PPI information is readily available to the operators.

This equipment was operated during the tornado seasons of 1957, 1958, 1959 and 1960 at Wichita Falls, Tex., and Wichita, Kans. Data were gathered from isolated thunderstorms, squall lines, the El Dorado, Kans., tornado of June 10, 1958, and from a large dust devil at Wichita Falls, Tex., on March 25, 1959.

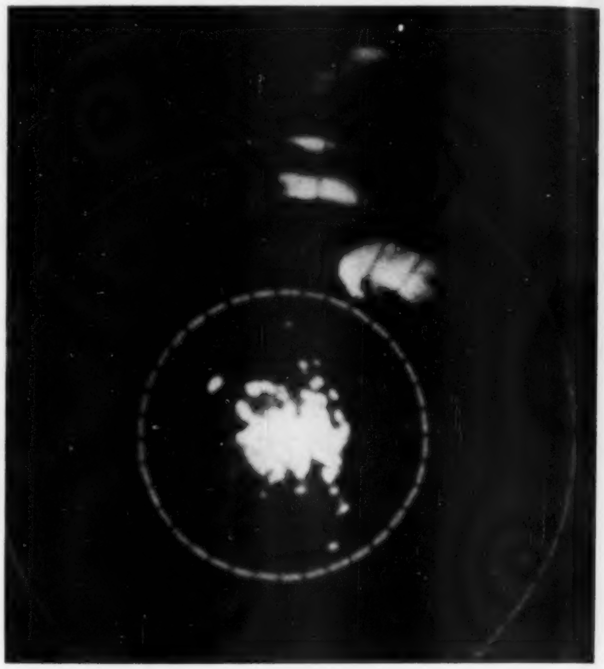

FIGURE 2.—PPI scope presentation (20-mi. range markers), 1700 CST, June 10, 1958 at Wichita, Kans., just before the time of the El Dorado tornado. Doppler radar was trained in direction of "hook".

2. DOPPLER PRINCIPLE

From elementary physics, one may recall the classic example of the Doppler effect as manifested by an approaching locomotive blowing its whistle. The trainman, being at the sound source, hears the true pitch of the whistle, while an observer down the track from the approaching train hears a higher pitch. The increase in pitch is the effect of the approaching locomotive, shortening the wavelength of the sound. From the emitted frequency f_0 the observer receives a frequency which is $f_0+\Delta f$, where Δf is the change in frequency caused by the motion of the locomotive. This small shift in frequency is called the "Doppler Effect" and is in a positive sense with an approaching sound source and in a negative sense with a departing sound source. The amount of Doppler shift is directly proportional to the speed of the sound source. The Doppler principle can also be applied to radar with the basic difference being that the speed of electromagnetic propagation rather than the speed of sound is involved. The Doppler radar equation is written:

$$\Delta f=\pm 2v\, f_0/c, \tag{1}$$

where Δf=Doppler frequency shift, v= radial component of target speed, f_0=transmitted frequency, and c=speed of light. Since the Doppler radar measures the magnitude of the Doppler frequency shift, this equation can be written:

$$v=|\pm \Delta fc/2f_0|. \tag{2}$$

It is emphasized that v is only the component speed parallel to the radar beam. This is often called the radial component, relative to the radar site. If the target is moving along the radar beam, v represents the true speed of the target. But if the target is moving at some angle other than that normal to the radar beam, v is some value less than the true speed of the target. If the target is moving normal to the beam, there is no Doppler effect $(\Delta f=0)$; therefore $v=0$. It is important to remember that v varies directly as $|\Delta f|$.

If the horizontal limits of a given vertical section of a tornado are wholly in the radar beam, the spectrum of Doppler frequency shifts will range from zero (particles moving normal to the beam) to some maximum value (particles moving along the beam). The signal strength of these frequencies decreases slightly with increasing frequency due to normal attenuation and shear effects assuming uniform distribution of particles about the tornado vortex, with the exception of large debris which should be randomly scattered.

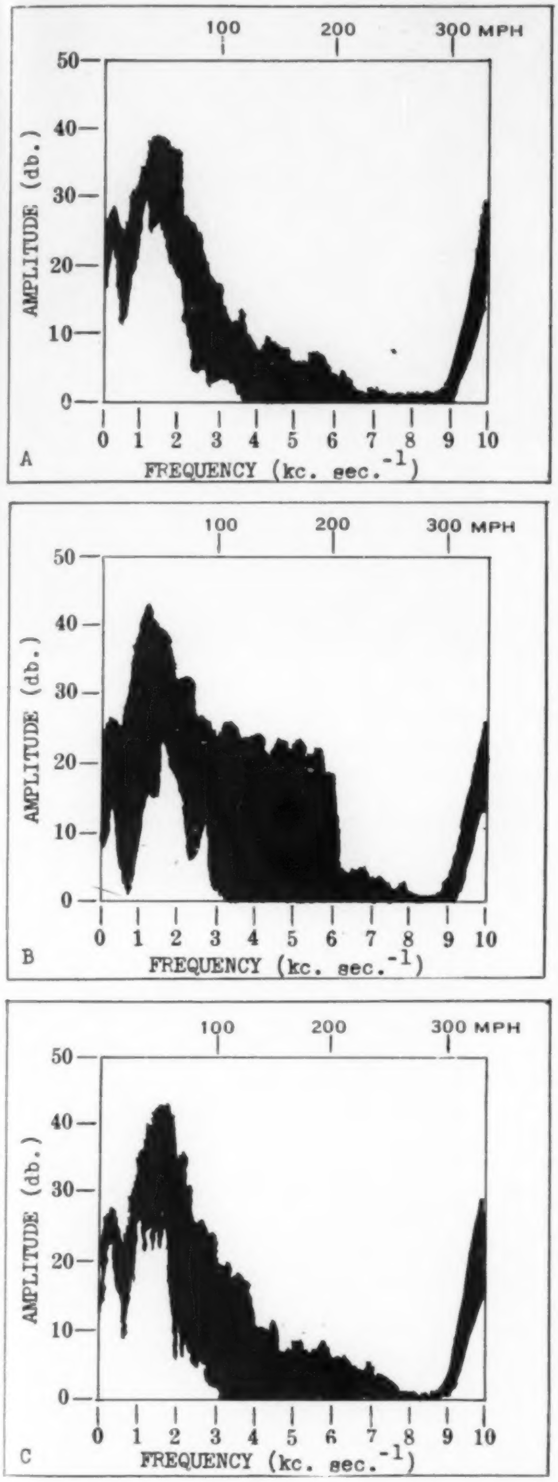

FIGURE 3.—Frequency spectrum analyses of Doppler radar signal near time of El Dorado tornado: (A) just prior to high speed signal, (B) during high speed signal, and (C) just after high speed signal.

3. DOPPLER OBSERVATIONS ASSOCIATED WITH THE EL DORADO, KANS. TORNADO OF JUNE 10, 1958

At approximately 1745 CST on June 10, 1958, a major tornado entered the city of El Dorado, Kans., killing 15 and injuring 50 persons. In addition, 150 buildings were destroyed, with total property damages amounting to an estimated \$3 million.

At approximately 1715 CST signals indicating high wind speeds were received at the Doppler radar operating at Wichita, Kans. The Doppler radar beam was trained in the direction of the "hook echo" then visible on the conventional radar repeater PPI scope inside the Doppler trailer. The picture in figure 2 was taken shortly before the high speed signals were received. The "hook" is located at an azimuth of about 30° and 22 nautical miles from the radar site. It has been confirmed that the funnel cloud, which later developed into the tornado that struck El Dorado (cf. [7]), was in existence at the time the Doppler signals indicating high wind speeds were received. This funnel was observed to be well defined both in shape and in circulation. The unique returns from the funnel at the Doppler radar were limited to a very short period because of equipment malfunction that developed shortly after the observation began.

Figures 3A, 3B, and 3C are reproduced records of the frequency spectrum obtained from the ultrasonic frequency spectrum analyzer. Figures 3A and 3C represent the analyzed returns from the parent thunderstorm, excluding the funnel, and appear like those of a typical thunderstorm, while figure 3B includes analyzed returns from the funnel. This series of indications occurred when the radar beam scanned slowly in azimuth through the funnel vortex. For several seconds, the analyzer indicated signals with a plateau appearance from about 2.40 to 6.15 kc. sec.$^{-1}$ (fig. 3B). During these several seconds there were distinct audio signals of higher pitches that correspond to the high frequency returns. The plateau effect in the higher frequencies occurred at an amplitude of about 15 db. below that of the lower frequencies, indicating that the particles rotating about the funnel vortex filled but a small percentage of the echoing volume of the beam. In addition, because the funnel was not touching the ground, it is assumed that there was nearly uniform distribution of particles about the vortex.

Since the signal strength of the returned energy is directly proportional to the number of particles in the radar beam, and because there were more particles moving at low speeds than at high, it seems that these are the primary reasons for the two general levels of amplitude shown in figure 3B. Of several possibilities of the beam position during its intersection with the funnel vortex, two are shown in figure 4. Due to the continuous horizontal and slight vertical scanning, the exact beam position in the vertical, with respect to the cloud base and funnel is not certain.

Calculations using equation (2) and the highest analyzed

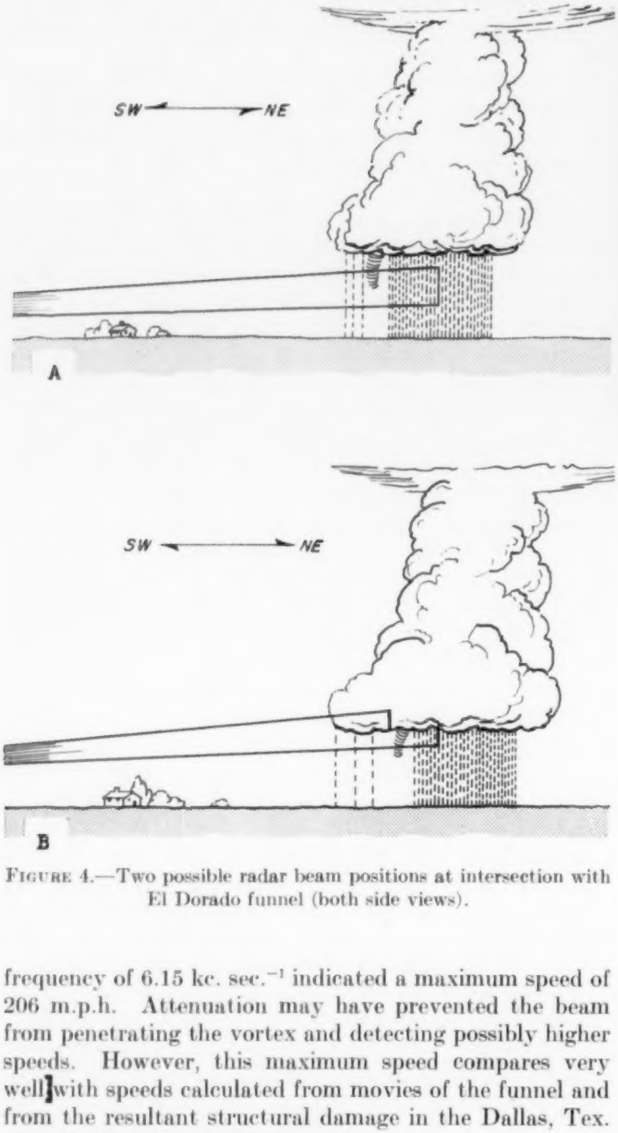

FIGURE 4.—Two possible radar beam positions at intersection with El Dorado funnel (both side views).

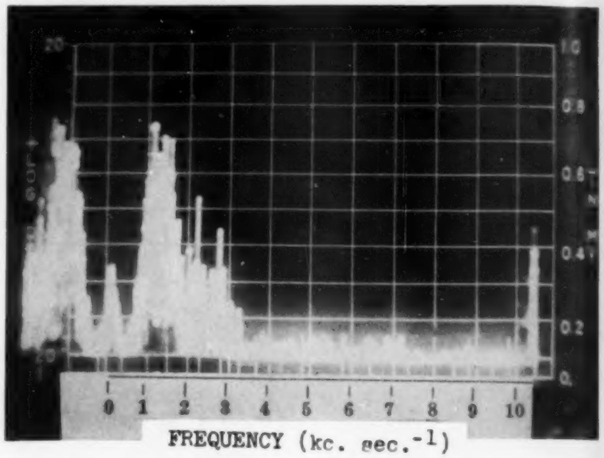

FIGURE 5.—Frequency spectrum analysis during dust devil occurrence at Wichita Falls, Tex., approximately 1410 CST, March 25, 1959.

frequency of 6.15 kc. sec.$^{-1}$ indicated a maximum speed of 206 m.p.h. Attenuation may have prevented the beam from penetrating the vortex and detecting possibly higher speeds. However, this maximum speed compares very well with speeds calculated from movies of the funnel and from the resultant structural damage in the Dallas, Tex. tornado of April 2, 1957 [2, 3, 5].

4. DOPPLER RETURNS FROM DUST DEVIL

At approximately 1410 CST on March 25, 1959, a large dust devil formed at Wichita Falls, Tex., about one-half mile from the Doppler radar site. It was about 50 yards in diameter and extended to about 300 feet above the ground. Frequencies up to 2.95 kc. sec.$^{-1}$ were indicated on the analyzer (fig. 5). Computations from the Doppler radar equation show that speeds up to 94 m.p.h. were recorded from this dust devil. Since a thunderstorm was in progress at the same azimuth and 15 miles from the radar site, signals were received from both. Those from the thunderstorm were from about 2,000 feet above the ground. The two general levels of amplitude are explained in the same way as in the case of the El Dorado tornado, with the added feature of low reflectivity of particles in the dust devil. Note that the plateau appearance exists due to the relatively uniform distribution of particles in the dust devil. The two narrow peaks of higher amplitude above the plateau might have been caused by a few large pieces of debris with greater reflectivity than the other particles in the dust devil. This case tends to support that of the El Dorado tornado in that the analyses are very similar.

5. SOME ADDITIONAL DATA GATHERED

In addition to the cases discussed above, data were gathered from many squall lines and isolated thunderstorms. Figures 6A and 6B show the PPI scope and analyzer presentations during the approach of a squall line at Wichita Falls, Tex. on April 16, 1959. The azimuth setting of the Doppler radar antennas was 290°, and the elevation angle was 0°. Indicated speeds were up to about 35 m.p.h.

Figures 7A and 7B show a case at Wichita Falls on May 9, 1959, in which high winds and hail were reported in the storm to the south. The Doppler radar antenna azimuth setting was 193° with the elevation angle ½°. Indicated speeds were up to about 65 m.p.h. near the surface in this storm. It has been observed that the region of maximum signal strength increases in frequency with increasing severity of the storm causing a shift of the spectrum to the right, due to higher velocities of a major portion of the particles.

During the 1959 season, some of the lower frequencies were excluded by use of frequency band-pass filters in the receiving system. This feature was added in order to let the higher frequencies become more audible to the operators, since the amplitude of the lower frequencies is

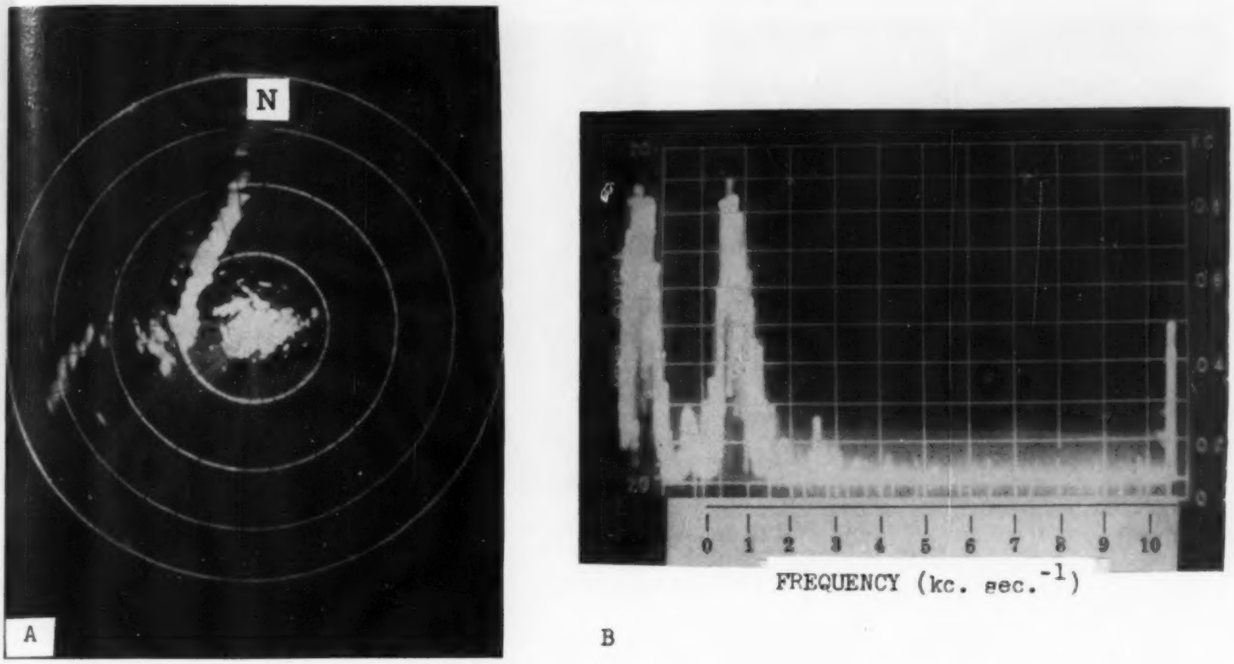

FIGURE 6.—(A) PPI scope (20-mi. range markers), at 2051 CST, and (B) frequency spectrum analysis at same time, during the approach of a squall line toward Wichita Falls, Tex., April 16, 1959.

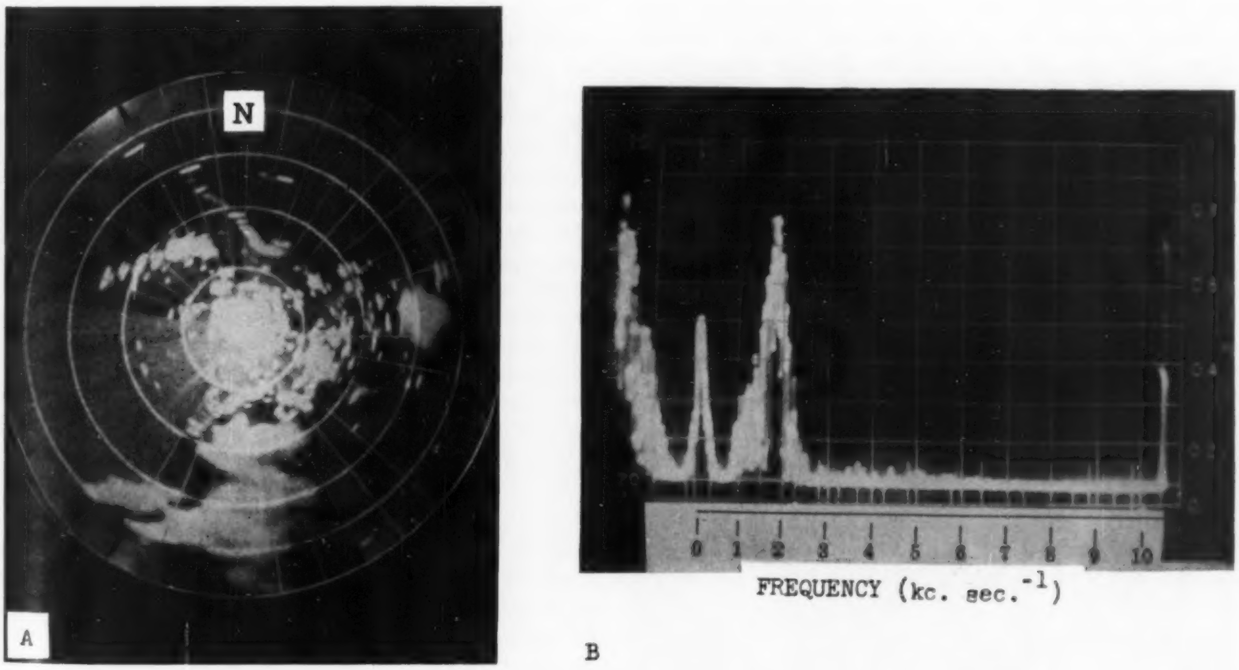

FIGURE 7.—(A) PPI scope (5-mi. range markers) at 2144 CST, and (B) frequency spectrum analysis, 2145 CST, May 9, 1959, at Wichita Falls, Tex. Hail and high winds were reported in the storm to the south.

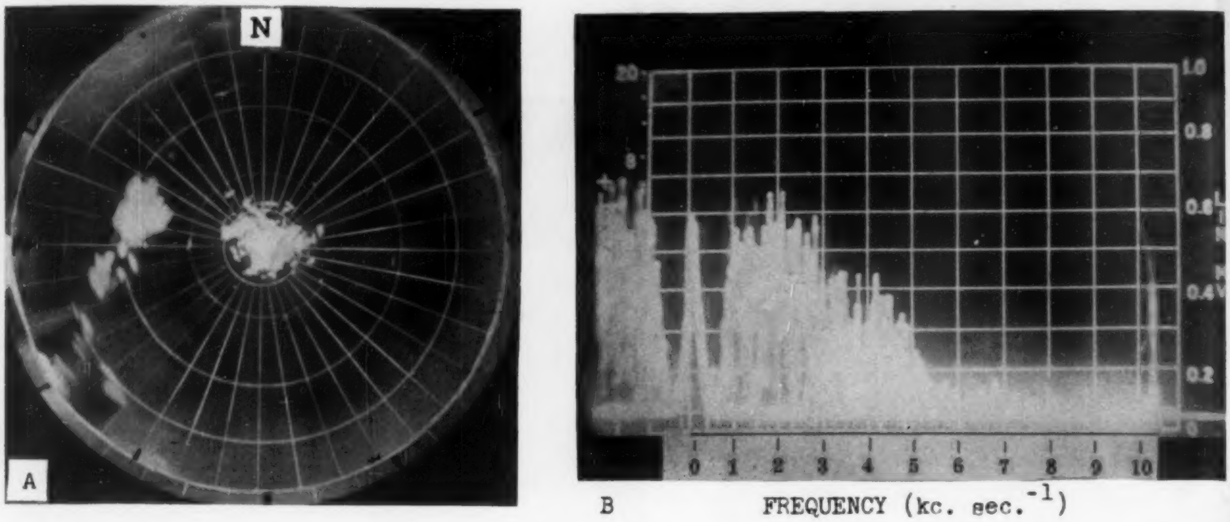

FIGURE 8.—(A) PPI scope (20-mi. range markers) at 1805 CST, and (B) frequency spectrum analysis, 1755 CST, May 19, 1959, Wichita Falls, Tex.

generally greater than that of the higher frequencies. The effect of these filters can be seen from the analyses made during the 1959 season, where the lower frequencies have been by-passed.

Figures 8A and 8B show a case where speeds were recorded from echoes about 32,000 feet above the ground in a large storm to the west of Wichita Falls on May 19, 1959. The azimuth setting of the Doppler radar antennas was 287° with an elevation angle of 10°. Indicated speeds were up to about 150 m.p.h. The significance of this figure is not understood at this time; however, it is possible that these speeds were from the anvil portion of the thunderstorm. It has been found that it is rather common to receive this type of return at these heights, but not in the lower levels, with the exception of funnel and dust devil cases. Further investigations of this phenomenon are being made.

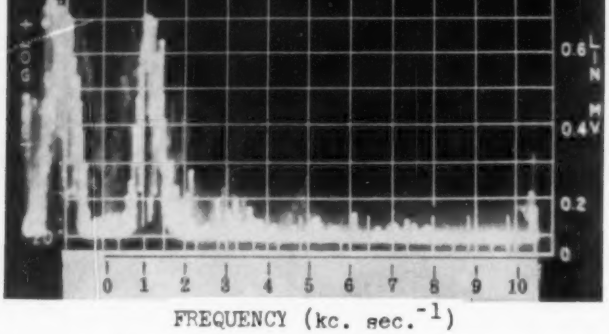

FIGURE 9.—Frequency spectrum analysis during heavy rain at the Doppler radar site.

Figure 9 shows the analyzer presentation when heavy rain was falling at the radar site. The elevation angle of the Doppler radar antennas was 4°, and indicated speeds were up to 45 m.p.h. It must be remembered that these speeds are the radial components, relative to the radar site, of the actual speeds of the targets. This is true in all three dimensions. This analysis represents return from rain drops only to a very short distance from the radar, due to severe attenuation. It was observed, that when light rain was occurring at the radar site, commercial aircraft of the Lockheed Constellation type could be tracked to a distance of only ¾ to 1 mile. In clear air they could be tracked to a distance of more than 30 miles. This reduction in detectable distances is, of course, due to attenuation, which is severe at this wavelength in precipitation. Therefore, when rainfall of over 0.10 inch per hour is occurring at the station the range of this radar is limited to less than 1 mile.

6. CONCLUSION

Although it appears, at this time, that Doppler radar is capable of detecting tornadoes, much additional evidence must be obtained before any firm conclusions can be reached. In addition, Doppler radar should be used for investigating cloud and clear air turbulence, velocities of falling rain, and detailed velocity patterns in hurricanes. Doppler radar might be used to determine precipitation rates in a manner similar to that used in conventional pulsed systems [1,4].

There are some major changes in the present equipment that should be made in order to have what would be considered an optimum Doppler radar for meteorological purposes. These are: (1) 5.4-cm. wavelength, (2) pulse instead of cw techniques, and (3) provision of "sense" to determine directions of motions.

The use of 5.4-cm. wavelength would reduce the attenuation problem considerably. Since there is a clear channel, 5600–5650 mc., assigned to meteorology, its use would reduce the chances of interference with other radars operating in the C-band.

The use of pulsed instead of cw techniques would allow for a tremendous increase in power output and energy penetration into storms. In addition, it would be possible to provide for range gating which cannot be done by using the cw technique. This is a very important feature, since with the reduced attenuation and increased power output, signals would often be received from two or more storms at the same azimuth from the radar site. For example, if the beam were intersecting a nearby storm at about 5,000 feet above the ground and a distant storm at about 40,000 feet above the ground, the signal return might be similar to a composite of figures 6B and 8B. This combination would appear very much like figure 3B. For this type of situation there are two possible explanations. Either a funnel or tornado exists in the nearby storm, or the high speeds are from the distant storm at high altitudes while the lower speeds are from the nearby storm. A Doppler radar system with range gating facilities would allow the operator to determine which case existed. It is worthwhile to mention, at this point, that at the time of the unique signals from the El Dorado storm, there were no other storms at the same azimuth within the range of the Doppler radar. The same is true for the storm 15 miles from the radar site, at the same azimuth as the dust devil.

Providing "sense" to the system is a feature that would show whether the Doppler shift was upward or downward in frequency, thus allowing the operator to determine if a majority of the particles were approaching or departing from the radar site. This would be especially advantageous in overhead turbulence studies in thunderstorms and in clear air.

One of the most critical problems that meteorologists have had to face has been to obtain reliable information concerning the actual existence of a tornado or funnel cloud in sufficient time to warn those in threatened areas. It is believed that Doppler radar would aid in easing this problem so that we can greatly improve our ability to prevent loss of life due to those storms.

ACKNOWLEDGMENTS

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Climatology at Work, Measurements, Methods, and Machines, edited by Gerald L. Barger assisted by John C. Nyhan, Washington, D.C., October 1960, 109 pp. For sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. Price 65 cents.

Describes the functions, scope, and capabilities of the centralized climatological facility located at Asheville, N.C. Chapter headings are: 1. Introduction—History and Development; 2. Climatology—Selected Elements of the Science; 3. Observations—Measurement, Enumeration, and Perception; 4. Methods—Summary, Graphical, and Statistical; 5. Machines—Processing and Computing; 6. The Product—Form and Availability.

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RAINSTORM IN SOUTHERN FLORIDA, JANUARY 21, 1957

ROBERT H. SOURBEER AND R. CECIL GENTRY

National Hurricane Research Project, U.S. Weather Bureau, Miami, Fla.

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ABSTRACT

The storm situation of January 21, 1957, is studied and the vorticity and horizontal divergence patterns are computed from analyzed synoptic maps at low and high elevations of the troposphere. Contour and streamline charts for the period are presented to show that consideration of many of the synoptic parameters ordinarily used in analysis and forecasting would not lead one to expect such heavy rainfall. Computations of divergence are compared with the rainfall charts in an effort to determine the cause of the heavy rainfall which varied in amount up to 21½ inches within a 24-hour period. The divergence patterns move horizontally with time in such a manner that a high-level divergence area becomes superimposed over a low-level convergence area at the time of heavy rain.

1. THE RAIN

Over 21 inches of rain fell in a limited area in southern Florida during a rainstorm on January 21, 1957. Figure 1 shows the rainfall distribution, in inches, for the storm. Amounts of 21.03 and 21.04 in. were recorded at West Palm Beach Water Co., gages 1–40 and 2–25, respectively, both of which are about 5 miles southwest of the West Palm Beach Airport. A few miles farther south a fall of 21.5 inches was recorded at the farm of Dan Smith. His gage is a small plastic one which reads to only 5 inches. However, Mr. Smith, watching the rain from a packing shed, dumped the gage each time it reached 4½ inches; this occurred 4 times with 3.1 additional for a total of 21.1. However, there was a spray barrel on the grounds which had been rinsed and drained the day before. After the rain (next day) Mr. Smith measured 21.5 inches of water in the barrel.[1] He stated that 16 inches fell between 11 a.m. and 4 p.m. EST.

Over 9 inches of rain fell at recording stations along the southeastern shore of Lake Okeechobee. Of these amounts an average of 6 to 7 inches fell between 4 a.m. and 10 a.m. EST, and less than 0.20 after 4 p.m. Five miles inland from Boca Raton, 17 to 18 inches of rain were recorded during the duration of the storm. Along the Atlantic Coast and at the Weather Bureau Airport Station at West Palm Beach the total was 6.33 inches, of which 4.70 inches fell between 5 p.m. and 7 p.m. EST, and only 0.04 after midnight.

The rainstorm as a whole moved from west to east. A time series of pictures taken of the radarscope at the University of Miami [1] shows that while the main rain cell was moving slowly eastward it was continually being reinforced by small cells that moved in from the east. (One picture is shown in fig. 2).[2] Rain cells dissipated as they departed to the west from the main rain core. This suggests that perturbations which triggered the beginning of showers were moving from east to west.

2. DATA FOR FORECASTING

Many of the parameters ordinarily considered in rain forecasting would indicate that little or no rain should have been expected on that particular day; e.g., the streamlines and contours at almost all tropospheric levels were either straight or had anticyclonic curvature. Only at 850 mb. and 500 mb. was there even weak cyclonic curvature, and

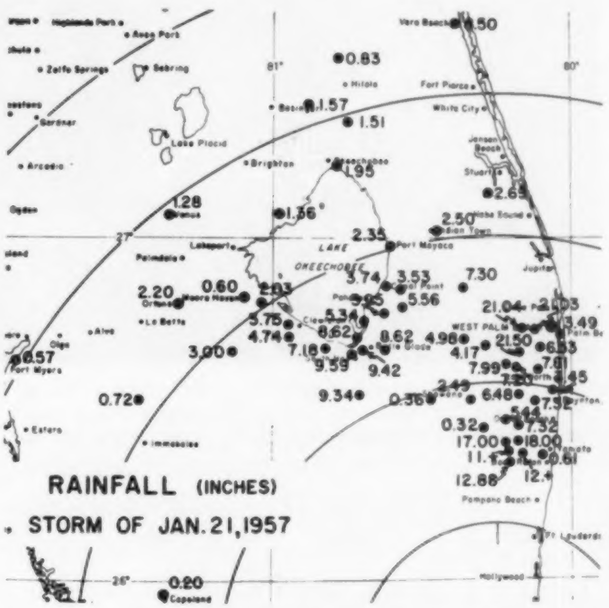

FIGURE 1.—Rainfall (inches) for the storm. Most of the rain fell in less than 24 hours. The very heavy rainfall lasted less than 5 hours at most stations.

[1] Reported by Jack L. Hudnall, Meteorologist in Charge, Weather Bureau Airport Station, West Palm Beach, after interviewing Mr. Smith.

[2] Prepared and analyzed by Mr. L. F. Conover from pictures taken at the Radar Laboratory, University of Miami.

FIGURE 2.—Pictures of radar scope taken at University of Miami, January 21, 1957. Echo "C" was quasi-stationary. Echoes "A" and "B" were moving toward the west-northwest at about 30 m.p.h. Note that the echoes moving westward out of the main rainstorm (echo "C") were relatively weak and dissipating. Echo "C" was over area where over 21 inches of rain fell.

at 700 mb. a weak ridge covered the area of intensive rainfall. Much of the cloudiness could be topped at 10,000 to 12,000 feet.

According to pilot reports there were isolated clouds that extended to great elevations. The soundings taken at Miami and Cocoa indicated the lapse rate was convectively unstable.

In this paper streamline maps at 2,000 feet and 250 mb., and maps of the divergence patterns at each of these levels, are reproduced. The heavy rainfall will be attributed to the divergence associated with the high-level jet over the area on January 21.

At the time of the heavy rain an area of divergence at the 250-mb. level, moving from the west-northwest,

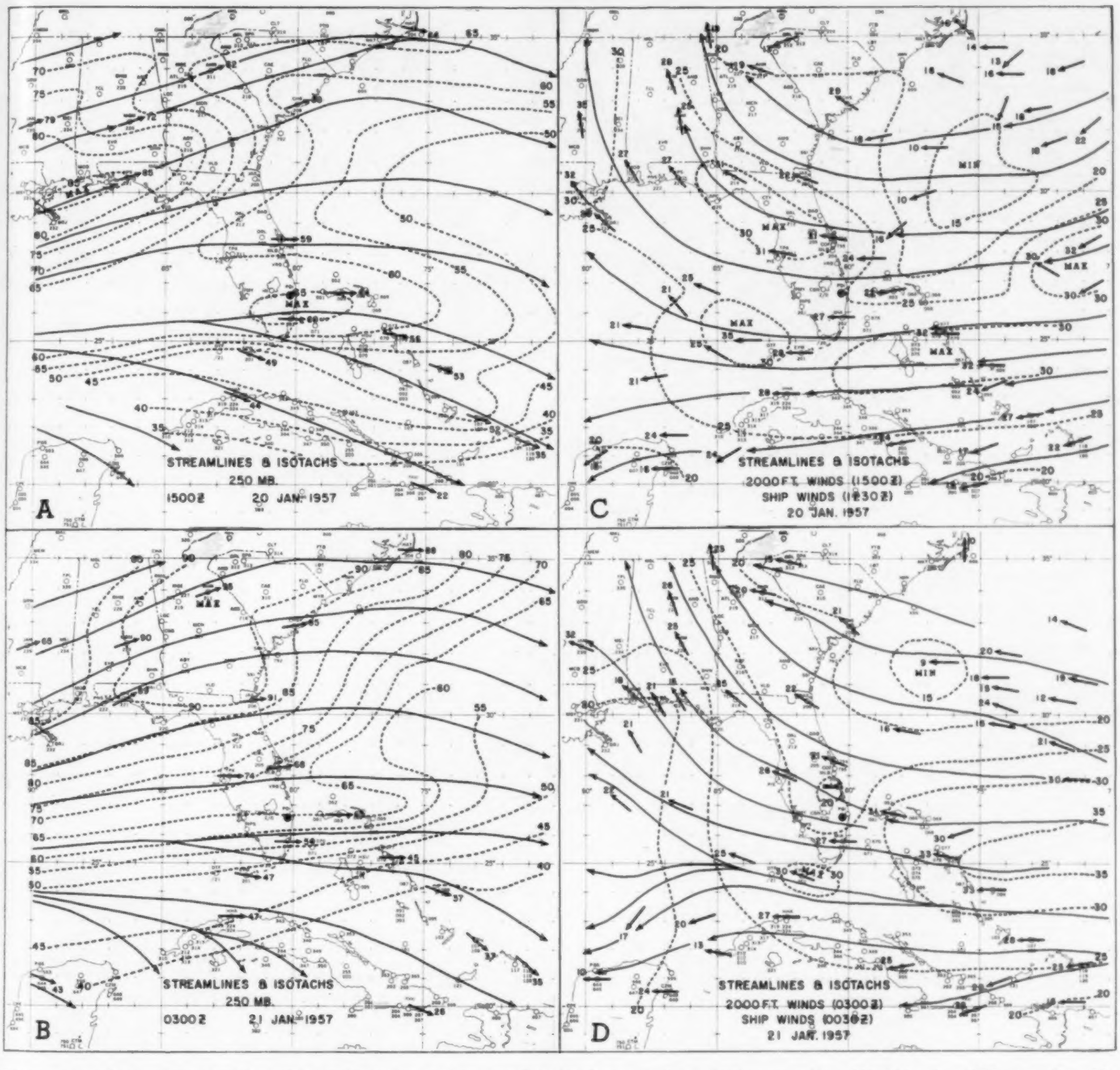

FIGURE 3.—Streamlines (solid) and isotachs in knots (broken) for the day preceding the heavy rain. (A) 250 mb., 1500 GMT, Jan. 20; (B) 250 mb., 0300 GMT, Jan. 21; (C) 2,000 ft., 1500 GMT, Jan. 20 (Ship winds at 1230 GMT); (D) 2,000 ft., 0300 GMT, Jan. 21, 1957 (Ship winds at 0030 GMT). The black dot near West Palm Beach marks the location of the heaviest rainfall.

arrived over the area coincident with the arrival of an area of convergence in the low-level wind field which moved in from the east-southeast. The time-lapse movies of the radarscope located at the University of Miami reveal a movement pattern of the echoes which lends support to these hypotheses.

Streamlines and isotach charts are presented in figures 3 and 4. (The heavy rain started a little before the time of the first two charts in figure 4 and was over by the time of the second two.) At both levels the streamlines are either straight or curved anticyclonically. The clue to the cause of the rain seems to be in the speed field. If the speed and moisture fields were omitted from these charts, there would be little to suggest that heavy rainfall would occur over southern Florida.

There are several features which are worthy of note. The decrease in speed in the low-level winds as they blew toward shore was undoubtedly a contributory cause of

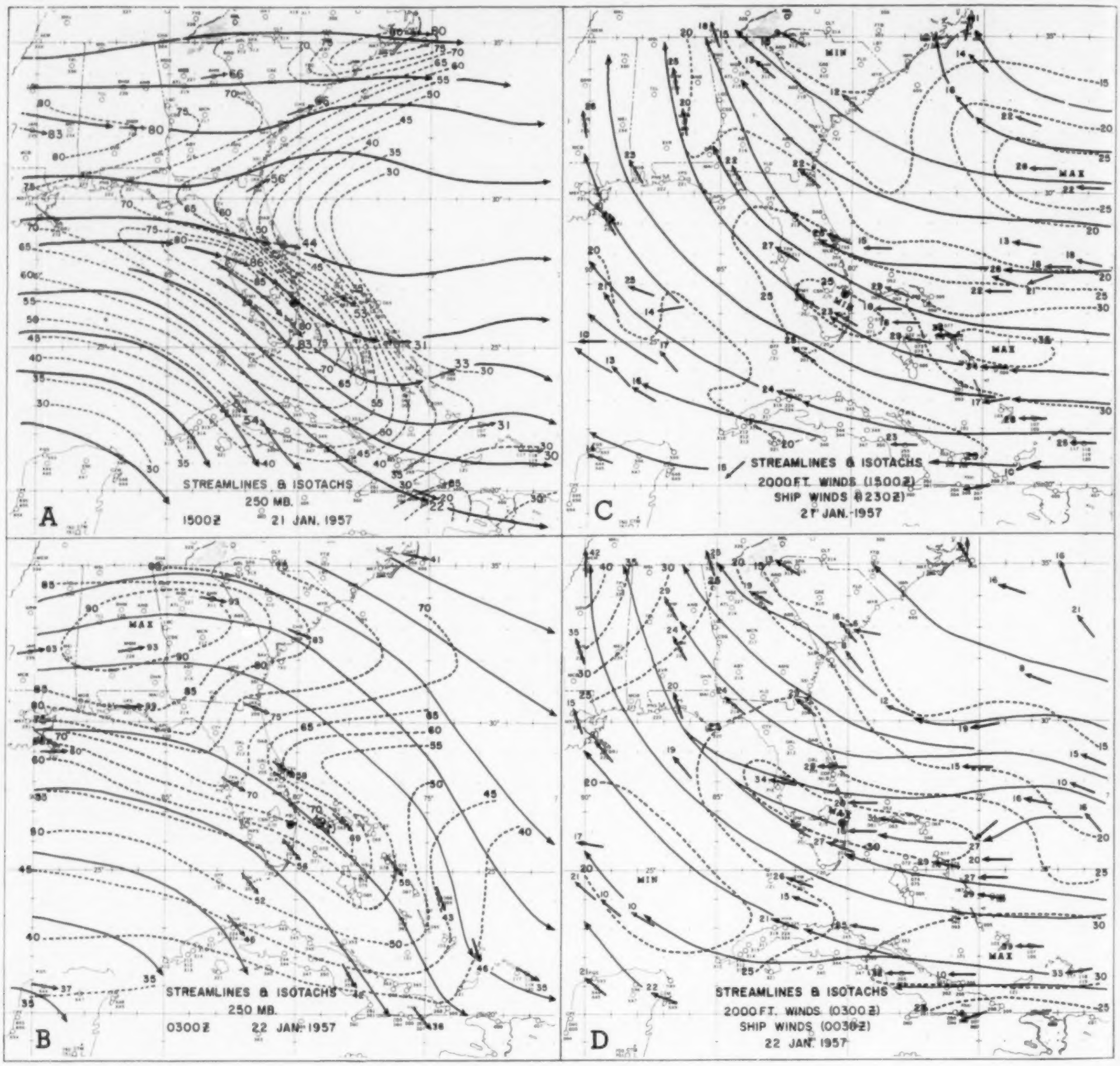

FIGURE 4.—Streamlines and isotachs (kt.) for the day of heavy rainfall. (A) 250 mb., 1500 GMT, Jan 21; (B) 250 mb., 0300 GMT, Jan. 22; (C) 2,000 ft., 1500 GMT, Jan 21 (Ship winds at 1230 GMT); (D) 2,000 ft., 0300 GMT, Jan. 22 (Ship winds at 0030 GMT). Black dot shows location of heaviest rain.

the rain. Note also the change at 250 mb. between 0300 GMT and 1500 GMT on the 21st (figs. 3B and 4A). The streamlines became more northwesterly and the jet stream very pronounced by 1500 GMT, at about the time the heavy rains began. Apparently the jet moved eastward across the state and weakened by 0300 GMT on the 22d, (fig. 4B) which is about 3 hours after the end of the heavy rain. The dot (figs. 3, 4, and 5) locates the area in which the rainfall was in excess of 21 inches. This was on the low pressure side of the jet stream and in advance of the maximum wind speed (fig. 4A). This is one of the areas (relative to the jet maximum) and the preferred one where, from vorticity considerations, one would expect to find divergence at the upper levels [2,3,4]. The argument of this paper is that the heavy rainfall was caused by the coincidence of divergence at high levels over the area of

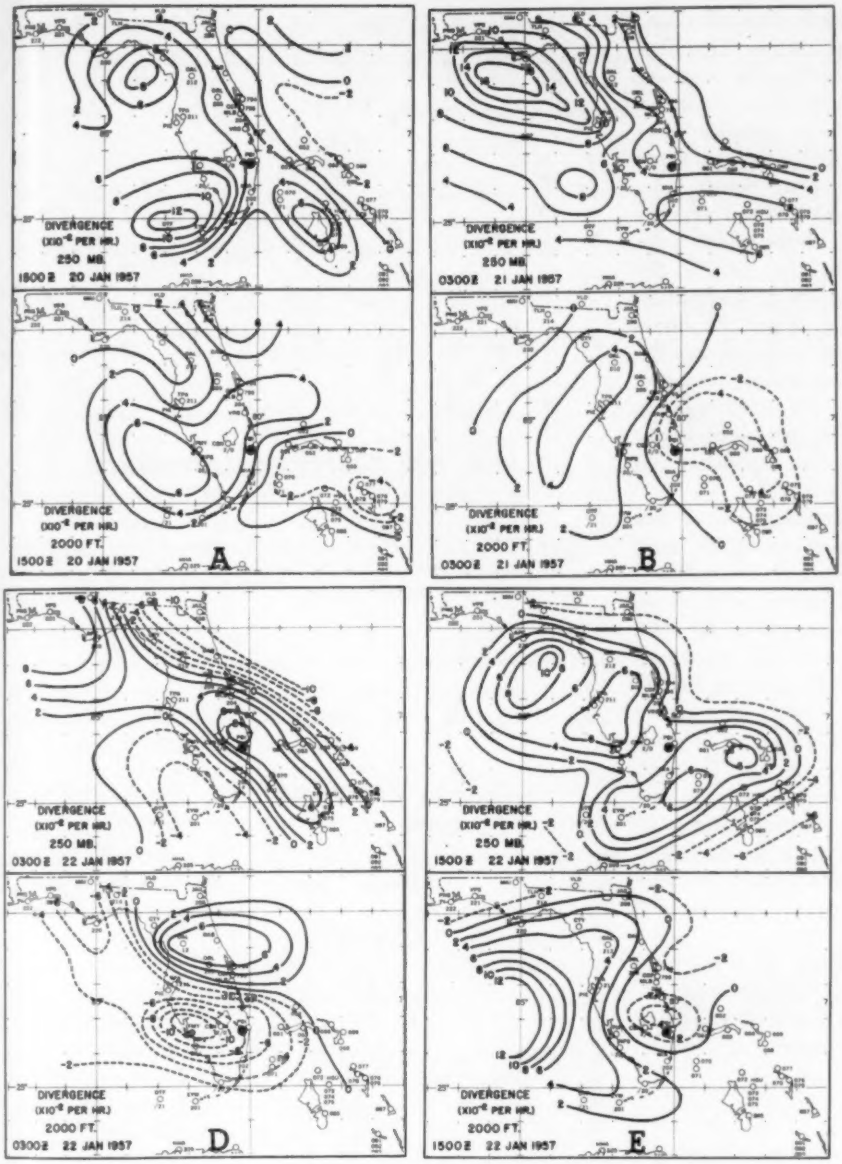

FIGURE 5.—Divergence (solid lines) and convergence (dashed lines) in units of 10^{-2} hr.$^{-1}$ for the 250-mb. level (upper chart of each pair) and the 2,000-ft. level (lower chart). (A) 1500 GMT, Jan. 20; (B) 0300 GMT, Jan. 21; (C) 1500 GMT, Jan. 21; (D) 0300 GMT, Jan. 22; (E) 1500 GMT, Jan. 22, 1957. Black dot shows location of heaviest rain.

convergence at the lower levels. It is the wind speed field which seems to bear the greatest causal relation to what happened in the weather.

3. HORIZONTAL DIVERGENCE COMPUTATIONS

The results of the computations of horizontal divergence made from the analyses are presented in figure 5. The divergence and vorticity were each computed with a Graham computer [5] for an equilateral triangular area of approximately 120 nautical miles altitude centered on each point in the grid shown in figure 6. (Vorticity charts are not reproduced.) Since the subjective analyses of the isogon and isotach charts influenced the computations, each of the wind charts was analysed by three analysts working independently. Although there were differences in values of divergence and vorticity at given points computed from the three independent isogon and isotach analyses, locations of areas of maximum and minimum divergence were approximately the same for any given time.

Consideration of the vertical moisture gradient existing over southern Florida at the time makes it clear that it

was necessary to have convergence in the first few thousand feet above the surface and ascending motion high into the troposphere for sufficient moisture to be removed from the air to account for the heavy rains observed. Thus for the period and area of heavy rainfall there should have been appreciable convergence in the lower layers (e.g., 2,000 feet), and in the upper layers (e.g., 250 mb.), and only one important layer of non-divergence in between. At the 250-mb. level, from 1500 GMT, January 20, to 0300 GMT, January 21 (fig. 5A–C), the strong area of divergence was building up in the eastern and northeastern Gulf of Mexico for about 24 hours before the heavy rains began. At 1500 GMT January 21, the area of divergence reached its maximum intensity and moved across southern Florida. By 0300 GMT on the 22d, (fig 5D) by which time the rain had about stopped, the divergence had decreased in intensity and moved off the southeastern coast of Florida.

At the lower level the area of convergence which was located off the southern Florida coast at 1500 GMT, January 20, (fig. 5A) expanded and moved westward until the leading edge was over Lake Okeechobee by 0300 GMT, January 21. At 1500 GMT, January 21, (fig. 5C) the area of convergence had become better organized with a more intense center just east of West Palm Beach. At 2100 GMT on the 21st (chart not shown), the center was about 30 miles northwest of Miami with greater values than those shown for 0300 GMT on the 22d (fig. 5D). From this series of charts, indications are that the convergence at low levels intensified rapidly shortly after 1500 GMT and moved westward across southern Florida, and then dissipated, except for a small area along the coast just north of West Palm Beach, between 0300 and 1500 GMT January 22.

Computations of divergence, necessary to account for the observed rainfall, can be used as an order of magnitude check on divergences computed from the analyzed wind fields. To a reasonably close approximation

$$-\overline{D}_i \approx \frac{gR}{\Delta p_i(\overline{q}_i - q_u)},$$

where $\overline{D}_i$ is the mean divergence in the inflow layer, g is acceleration of gravity, R is rainfall rate, Δp_i is difference in pressure between top and bottom of the inflow layer, $\overline{q}_i$ is mean specific humidity of air in the inflow layer, and q_u is specific humidity of moisture flowing out of the rain area. From 1500 GMT January 21 until 0300 GMT January 22, average areal rainfall for a triangle of the size indicated in figure 6 in the area of greatest rainfall was about 0.1 cm./hr. If $\Delta p_i = 150$ mb., $\overline{q}_i = 11$ gm. kg.$^{-1}$ (indicated by the soundings), and $q_u = 3$ gm. kg.$^{-1}$ (assumed) the convergence in the inflow layer is approximately 8×10^{-2} hr.$^{-1}$. This is the same order of magnitude as the maximum values of convergence on the charts in figure 5. At the Dan Smith farm, rain fell at the rate of about 9 cm. hr.$^{-1}$ between 11 a.m. and 4 p.m. If the same assumptions for Δp_i, q_i, and q_u are used, the mean

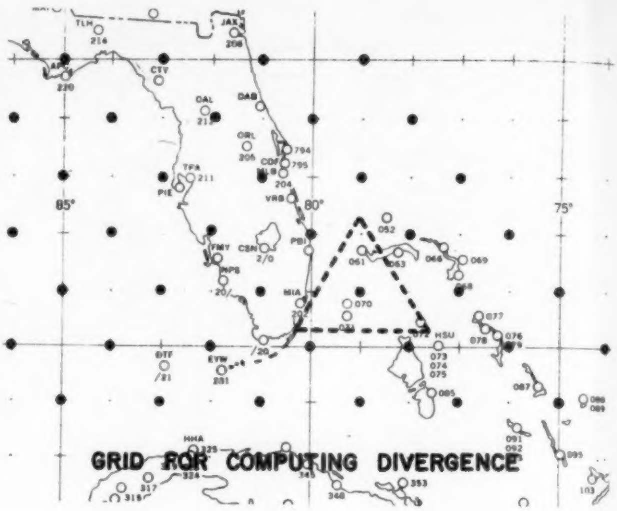

FIGURE 6.—Grid for which divergence computations were made. Computations were made for areas the size of the triangle, centered at each heavy dot.

convergence in the inflow layer is approximately +7.4 hr.$^{-1}$. This is obviously much greater than any convergence indicated by the wind reports, and mass compensa-

TABLE 1.—*Horizontal divergence (10^{-2} hr.$^{-1}$), January 20–22, 1957*

Height 10^3 ft.	January 20	January 21		January 22	
	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT
A. Miami, Cocoa, Grand Bahama Triangle					
50	5.40	15.05	−5.94	8.82	1.44
40	−2.70	5.83	25.70	−1.04	−34.20
(250 mb.)	0.11	13.75	32.72	19.76	10.19
30	−0.54	5.83	24.12	8.68	1.40
25	9.11	−3.49	18.61	−2.66	3.13
23	3.56	4.14	21.38	0.22	
20	8.96	5.54	1.12	14.54	0.61
18	16.20	8.93	−2.99	5.04	−3.24
16	7.20	4.10	−6.84	15.05	−1.55
14	−0.54	8.81	−7.20	11.95	−7.20
12	1.12		−11.45	9.40	2.59
10	1.69		−12.85	−0.54	4.46
8	−4.39		−4.64	−2.99	−4.18
6	3.82		−6.44	4.03	1.76
5	4.39		−8.32	−0.40	−1.73
4	1.66		−2.48	−8.42	0.32
3	1.04		−5.11	−3.02	
2	8.86		−7.67	−10.69	4.61
1	8.71	9.68	−7.63	−10.04	−1.80
B. Miami, Cocoa, Tampa Triangle					
50	−13.39			−4.72	−8.17
40		5.29	7.99	1.08	−19.66
(250 mb.)	4.39	−0.50	3.02	−3.31	19.84
30	−3.17	10.87	24.41	−12.35	−4.72
25	−6.48	1.98	30.78	−1.40	0.50
23	−10.48	3.20	23.18	11.63	−4.00
20	0.54	0.72	20.23	20.59	0.07
18	4.21	10.66	23.62	12.92	−3.38
16	−0.58	0.32	4.18	11.27	5.81
14	2.05	4.28	11.20	−6.84	11.02
12	1.01		−5.15	−3.49	11.74
10	−2.66		−1.22	−21.49	16.42
8	−11.38		7.92	−17.89	−0.04
6	−3.82		1.73	−9.43	1.08
5	4.00		−1.01	−3.85	−6.66
4	5.80		−6.55	−5.26	−8.71
3	1.08		−6.52	0.58	−2.41
2	3.96		−1.58	1.69	0.76
1	0.40	3.89	−5.44	−2.38	−1.32

tion in the vicinity of the torrential rain must have taken place within a much smaller area than that of the triangles considered in this study.

To check the validity of the divergence computations which were made from subjective analyses, the winds at Cocoa, Grand Bahama, Miami, and Tampa were used to compute in an objective manner the divergence for two triangular areas [6]. In table 1 the results of these computations are presented for the same times as the 250-mb. and 2,000-ft. charts. Table 1A gives the divergence computations for the Miami, Cocoa, and Grand Bahama triangle. Table 1B is for the Miami, Cocoa, Tampa triangle. Note at 1500 GMT on the 21st, near the time of the beginning of the heavy rain, the extremely large values of divergence at upper levels and the convergence at low levels. In general the objective computations of divergence support the more detailed computations based on the subjective analyses.

The vertical motion (averaged over the area) can be computed from the divergence values given in table 1 by using the trapezoidal rule [6],

$$w_n = w_{n-1}\frac{\rho_{n-1}}{\rho_n} + \left[D_{n-1}\frac{\rho_{n-1}}{\rho_n} + D_n\right]\frac{\Delta z}{2},$$

where w is vertical velocity, ρ is density, D is divergence, subscripts n and $n-1$ refer to levels, and Δz is thickness of layer. These computations can be made either by letting $w_0=0$ or by assuming w at the height of the tropopause (about 40,000 feet) to be the same as the mean change in height of the tropopause for a 24-hour period centered on time of observation. Maximum vertical velocities given by these computations are given in table 2. In three of the four cases the maximum tropospheric vertical velocities computed from the two different boundaries are of the same order of magnitude. Differences are probably due to the winds at the vertices of the triangles not being completely representative of the wind field along the sides of the triangles or of the layers between the reporting levels, or to wind direction being reported only to 10 degrees.

In general the changes in the divergence patterns about the time of heavy rainfall were more prominent at the upper than at the lower levels. The time changes in the maximum vertical velocities computed on the assumption that w at 40,000 feet equals w of tropopause were more closely correlated with changes in intensity of the rainfall in the respective triangles than were the maximum velocities computed with $w_0=0$. Thus, for this case,

TABLE 2.—*Vertical motions (cm. sec.$^{-1}$), January 21–22, 1957*

	Miami, Tampa, Cocoa triangle		Miami, Cocoa, Grand Bahama triangle	
	1500 GMT Jan. 21	0300 GMT Jan. 22	1500 GMT Jan. 21	0300 GMT Jan. 22
w of tropopause* (cm. sec.$^{-1}$)	+2	+1	+1	+1
Maximum vertical velocity in troposphere computed with $w_0=0$	+2	+13	+18	+4
Maximum vertical velocity in troposphere computed by assuming w at 40,000 feet = w of tropopause	+26	+5	+37	+10

*Mean rate of change of height of tropopause for 24-hour period centered on time of observation.

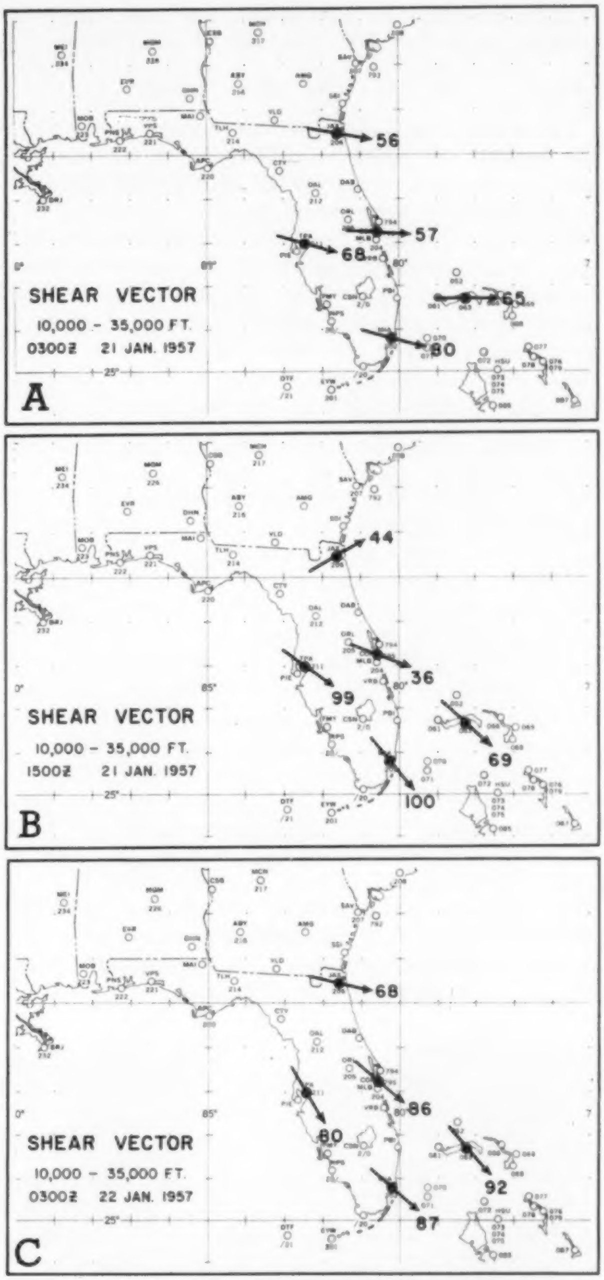

FIGURE 7.—Vertical wind shears (kt.) 10,000–35,000 feet. (A) 0300 GMT, Jan. 21; (B) 1500 GMT, Jan. 21; (C) 0300 GMT, Jan. 22, 1957.

changes in the divergence patterns in the upper troposphere gave strongest clues concerning rainfall prediction.

4. VERTICAL WIND SHEAR

The vertical wind shear was very strong on the day of the rainfall. In figure 7 we have the charts from 0300 GMT on the 21st through 0300 GMT on the 22d. The 10,000–35,000-ft. wind shears range in value from 36 to 100 kt. in this period. These shears, just as did the divergence computations, strongly suggest that extreme vertical motion was taking place [7, 8]. The strong shears indicate intense thermal gradients and the observed winds should have caused greater advective warming in the upper troposphere than was recorded at fixed levels. Therefore, the shears give indications of ascending motion.

5. CONCENTRATION OF RAINFALL

It is believed that juxtaposition of land and water masses helped keep the heavy rainfall in the relatively small area between West Palm Beach and Lake Okeechobee for several hours. Particularly in the low levels the winds would be subject to less frictional drag while blowing over the ocean surface than over land. Thus the air blowing from the ocean to land naturally would have established convergence patterns near the coast. As the air again blew over water, i.e., Lake Okeechobee, there would have been an acceleration of the wind speed and increased divergence due to less frictional drag. The radar pictures [1] (also see fig. 2) indicate that for several hours small showers developed near and just east of the Atlantic Coast, moved westward into the hard core rain area, and dissipated as they moved farther westward. This suggests that the low-level wind field was triggering the showers and that the high-level wind field with its intense divergence pattern was accelerating the vertical motion and causing the rain to be so heavy.

6. CONCLUSIONS

Synoptic evidence supports the hypothesis that the heavy rain was caused by the superposition of a high-level area of divergence over a low-level area of convergence. The location of the rain was influenced by the location of the land and water masses.

If we are to attempt to forecast such heavy localized rainfall and, in particular, to identify the area in which the heavy rainfall will occur, we will need better techniques for forecasting the formation and movement of high-level jet streams and particularly the microstructure features of the speed field in the jet stream.

ACKNOWLEDGMENTS

The authors are indebted to the University of Miami Radar Meteorological Laboratory (Mr. Homer W. Hiser, Director) for permission to study the time-lapse pictures of the radarscope (assembled and edited by Mr. L. F. Conover). They also had valuable discussions of the work with several members of the staff of the National Hurricane Research Project, and Drs. H. Riehl, N. E. LaSeur, and Charles L. Jordan.

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Weather Note

RADAR ECHO OF A MOUNTAIN WAVE ON FEBRUARY 15, 1960

DEVER COLSON, CHARLES V. LINDSAY, AND JAMES M. HAND

U.S. Weather Bureau, Washington, D.C.

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1. INTRODUCTION

There have been many descriptive accounts of mountain wave cloud patterns, but to our knowledge such clouds have not been previously observed on radar. Since the new WSR–57 radar has been installed at Washington National Airport, the authors have been watching wave situations to see if some indications could be seen on the radar. At 1330 EST on February 15, 1960, a wave cloud pattern was observed on the range-height-indicator (RHI) scope. Figure 1 shows a Polaroid picture of the radar scope.

2. OBSERVED EVIDENCE OF THE WAVE

On the previous day, perfectly formed standing wave lenticular altocumulus clouds were observed overhead and to the northwest of Washington around 1330 EST following a general clearing after snow had ended in the area. The clouds were oriented northeast-southwest and at least four waves were observed. These lasted until around 1700 EST by which time most of the clouds had dissipated.

Considering the fact that conditions were again favorable for wave formation on the morning of February 15, it was not surprising that a Navion reported severe turbulence at 10,000 feet over Frederick, Md. at 0800 EST. A Martin 404 reported severe turbulence at 7,000 feet over Albany, N.Y. at 0815 EST. Lynchburg, Va. reported standing wave lenticular altocumulus clouds to the north over the mountains from 1100 to 1400 EST. Several other stations reported lenticular altocumulus clouds. A strong downdraft was reported by a DC–3 at 6,000 feet southwest of Montpelier, Vt. at 0859 EST. Martinsburg, W. Va. reported scattered clouds at 8,000 feet and overcast conditions at 12,000 feet. See figure 2.

The clouds as viewed from Washington National Airport were altocumulus floccus with a considerable amount of virga in the form of snow. The snow seemed to fall straight from the clouds and then trail away to the southeast. The clouds, whose tops appeared to be very flat, extended as far west as could be seen. By late afternoon, there appeared to be two rows of wave-shaped clouds to the west. Smaller fragments of the altocumulus clouds continued to drift eastward but none reached the area over the airport.

3. WAVES AS SHOWN ON THE RHI SCOPE

The photograph of the RHI scope (fig. 1) shows that the top of the echoes was near 18,000 feet. The height of the bases apparently increased from 7,000 feet on the western end to about 12,000 feet at the eastern end with the cells becoming smaller to the east. The picture shows 8, to possibly 11, waves spaced about 3½ miles apart with a missing echo between the last two cells at the eastern end. The gap may simply mean that this cell was quite weak and was dissipating as fast as it could form or that the air was locally quite dry in this region. The last broad echo over the mountains to the west of Martinsburg, with tops around 14,000 feet, appears to be from an area of more general cloudiness possibly with precipitation reaching to near the ground.

4. SUPPORTING UPPER AIR DATA

Because the observed weather and cloud patterns overhead at the Washington National Airport were decidedly different from those to the west, it is felt that the Wash-

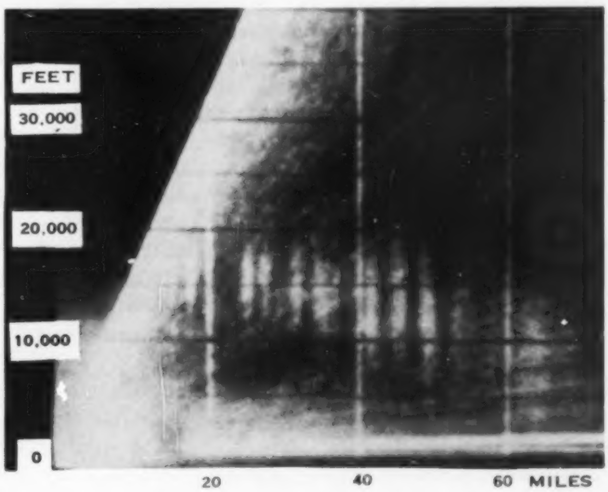

FIGURE 1.—Radar scope presentation, 1330 EST, February 15, 1960, at Washington National Airport, Washington, D.C.

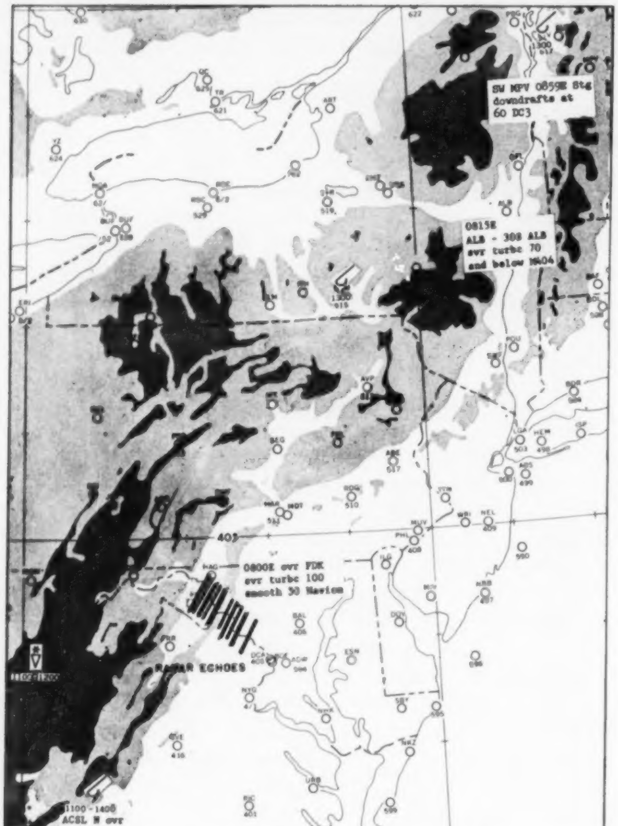

FIGURE 2.—Map showing the observations indicating turbulence on the morning of February 15, 1960 and the plotted position of the radar echoes seen at Washington. Shading shows topography.

ington sounding was not very representative of the echo area. The nearest soundings were the Pittsburgh 0700 EST and the Washington 1300 EST observations. The sounding at Pittsburgh (fig. 3) showed several stable layers from the surface up to 7,000 feet and between 10,000 and 12,000 feet with increasing winds above 12,000 feet. If the moisture, as indicated on the morning Pittsburgh sounding, was lifted to saturation, clouds similar to those shown on the radar could have been produced.

The Washington sounding (fig. 4) taken at 1300 EST showed stable layers from 6,000 to 10,000 feet, and again at the 13,000 and 17,000-foot levels with a decided increase in wind speed above 6,000 feet. The air was quite dry between 6,000 and 13,000 feet.

Work by Scorer [5] shows the importance of atmospheric stability in the establishment of waves. His stability term is given by $l^2=g\beta/U^2$, where U is the wind speed, β the static stability, and g is gravity acceleration. According to Scorer l^2 should decrease in the upper layer over that in the lower layer. In this case for the 1300

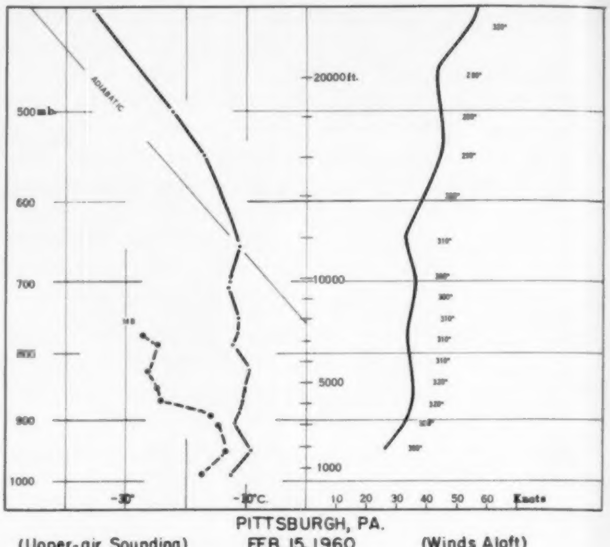

FIGURE 3.—Upper air sounding and winds aloft at Pittsburgh, Pa.

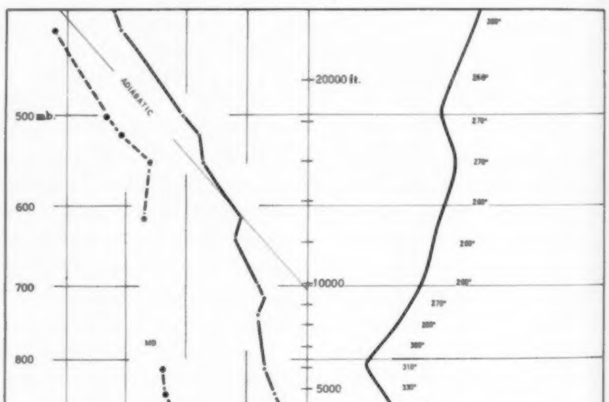

FIGURE 4.—Upper air sounding and winds aloft at Washington, D.C.

EST Washington sounding l^2 was equal to an average of 3.2 below 10,000 feet and 0.6 above that level. For the 0700 EST Pittsburgh sounding l^2 was equal to an average of 2.3 below 12,000 feet and 0.7 above that level.

On this particular day a strong jet stream was oriented in about a west-east direction over southern Virginia. Colson [1] pointed out that the presence of a strong jet stream in the higher levels is the most probable situation

giving rise to the strong wind shear which is essential in the formation of mountain waves.

On the assumption of increasing moisture in the middle layers as the air moved eastward and the strengthening of the inversion near the 10,000-foot level as indicated on the Pittsburgh sounding, along with the stronger wind speeds and wind shear as indicated on the Washington sounding, a computation of the wavelength of billow clouds using the equations developed by Haurwitz [3, 4] gives values of the wavelength of the correct order of magnitude, 2 to 3 miles. The wavelength observed on the RHI scope was approximately 3½ miles. In another report on a very prominent wave cloud system in this area by Colson and Lindsay [2], the wavelength was computed to be about 4 miles.

5. CAPABILITIES OF THE WSR-57 RADAR

Much valuable information can be derived from the radar equipped with the RHI scope. Through its use a three-dimensional representation or interpretation of the radar echoes can be made. However, there are several factors which must be taken into account before definite quantitative measurements can be made. These include the characteristics of the particular radar set, the nature of the echoes, corrections for earth's curvature and beam width distortion. In making these corrections one must be sure that the targets are filling the radar beam and that the normal signal propagation is maintained. The problem of getting a representative picture of all of the targets at one time is difficult because if only the edge of a target is being scanned, it will appear noticeably smaller or weaker than other targets more completely in the beam. However, it was not felt worth while to make the detailed corrections in this case, since we are mainly interested in a qualitative interpretation of the radar picture.

Because of the vertical motions involved in the formation of wave clouds, these can support larger water droplets than ordinary altocumulus clouds and are better targets for the radar beam. The ability of radar to indicate the location and extent of wave phenomena could be a useful tool in aviation forecasting. Mountain waves present a serious hazard to small aircraft and also to larger aircraft whose operational requirements demand that flights be made at levels close to the terrain. In some cases, mountain waves generate severe turbulence and strong updrafts and downdrafts.

6. CONCLUSIONS

The results of observations during the past years indicate that the mountain wave situations can be rather widespread and particularly frequent during the winter months east of the Appalachians. Further efforts will be made at Washington National Airport to obtain additional data of this nature to determine the possibilities of radar in the detection of wave clouds.

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CORRECTION

Monthly Weather Review, vol. 88, Aug. 1960, pp. 290–291: In Section 4, Monthly Mean 700-mb. Circulation, the reference to the map of monthly mean circulation in line 2 should be to figure 7; the figure referred to in line 8 from the bottom of that column should be figure 6. P. 291, line 8, col. 1: reference should be to figure 7.

Weather Note

TORNADOES NEAR NAGS HEAD, N.C., IN MAY AND JUNE 1960

FRANK B. DINWIDDIE [1]

Nags Head, N.C.

[Manuscript received July 18, 1960; revised November 4, 1960]

1. TORNADOES ON MAY 11, 1960

A family of suspended funnel clouds and accompanying pendants was seen at Nags Head on May 11, 1960, between 1520 and 1530 EST. Surface conditions at the time were: wind light and variable, from directions east, south, and west. Shortly after the episode the wind became SSW about 10 m.p.h. and continued thus. Station pressure was 29.82 in. mercury, and rising slowly, temperature 70° F., steady, dew point 56° F., and relative humidity 64 percent. Before the occurrence of the funnels, cumuli moved from the peninsula between Pamlico and Albemarle Sounds and formed into a band, but there was no squall activity or sudden wind or temperature change. The band of cumulus congestus formed nearly overhead in a west-southwest to east-northeast direction and moved along its long axis. No thunder or lightning occurred in connection with these tornado-forming clouds. The congestus clouds in the line formation were not especially massive, and yet a few drops of rain fell from the line at 1445 EST, 35 minutes before the occurrence of these tornadoes. Just after the tornadoes a shower formed a few miles to the west, moved over my location, and gave 0.02 in. of rain. After that the cloud cover diminished. Figures 1, 2, and 3 described in the following discussion were traced from projected color transparencies of these funnels.

During the existence of these tornadoes the base of the cumulus congestus band was rather smooth and straight. There were no waves, bends, roll clouds, or agitation observed here as was seen with an earlier tornado occurrence [1] at Nags Head. The funnel circulations did not extend outward into the associated cloud to any extent and were observed positively only in funnels labeled C and F in figure 1, and D–1 and F in figure 2. Updrafts were also observed with these three vortices which tapered to sharp points. The pendant clouds, labeled B, D, and E, were bulbous in appearance, exhibited downdrafts, but had no rotation. In the time between figures 1 and 2, the vortex D–1 formed to the right of pendant D. In figure 1 seven, and in figure 2 eight, pendants were labeled but the significant feature is the apparent existence of three pairs of pendants (B, C and E, F in fig. 1, and D, D–1 in fig. 2) possibly associated dynamically. Each pair consisted of a twisting, pointed funnel with associated updraft, while by its side (to the left, or northeast) was a bulbous pendant with downdraft. The first pair in

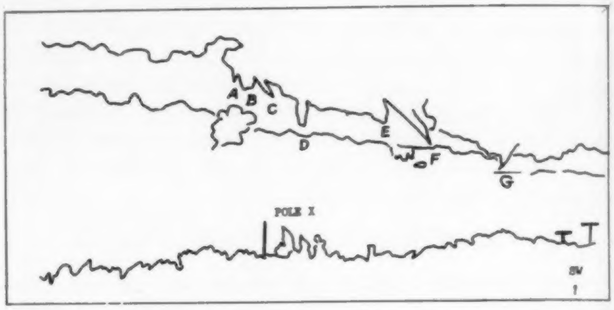

FIGURE 1.—Tornado family at Nags Head, N.C., May 11, 1960, 1520 to 1530 EST. The figure was traced from a projected color transparency. Note vortices C, F, and G, and pendants B, D, and E. Pendant B and vortex C are paired as are E and F.

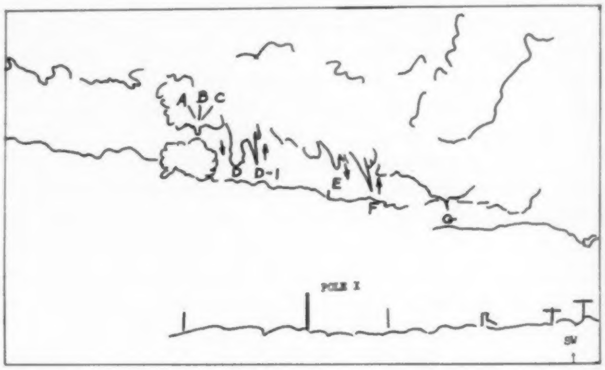

FIGURE 2.—Second traced view of tornado family a few minutes after figure 1. Note the pendant-vortex pairs D and D–1, and E and F. By now, A, B, and C have become one pendant or vortex. Downward motion was associated with D and E, and upward motion and rotation with D–1 and F.

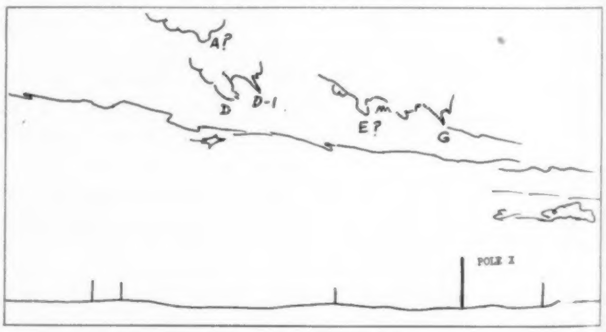

FIGURE 3.—Tornado family 10 minutes after figure 1, again traced from a transparency. Pendant D and paired vortex D–1 remain, pendant E apparently remains, and pendant or vortex G still exists.

[1] Cooperative Weather Observer, U.S. Weather Bureau.

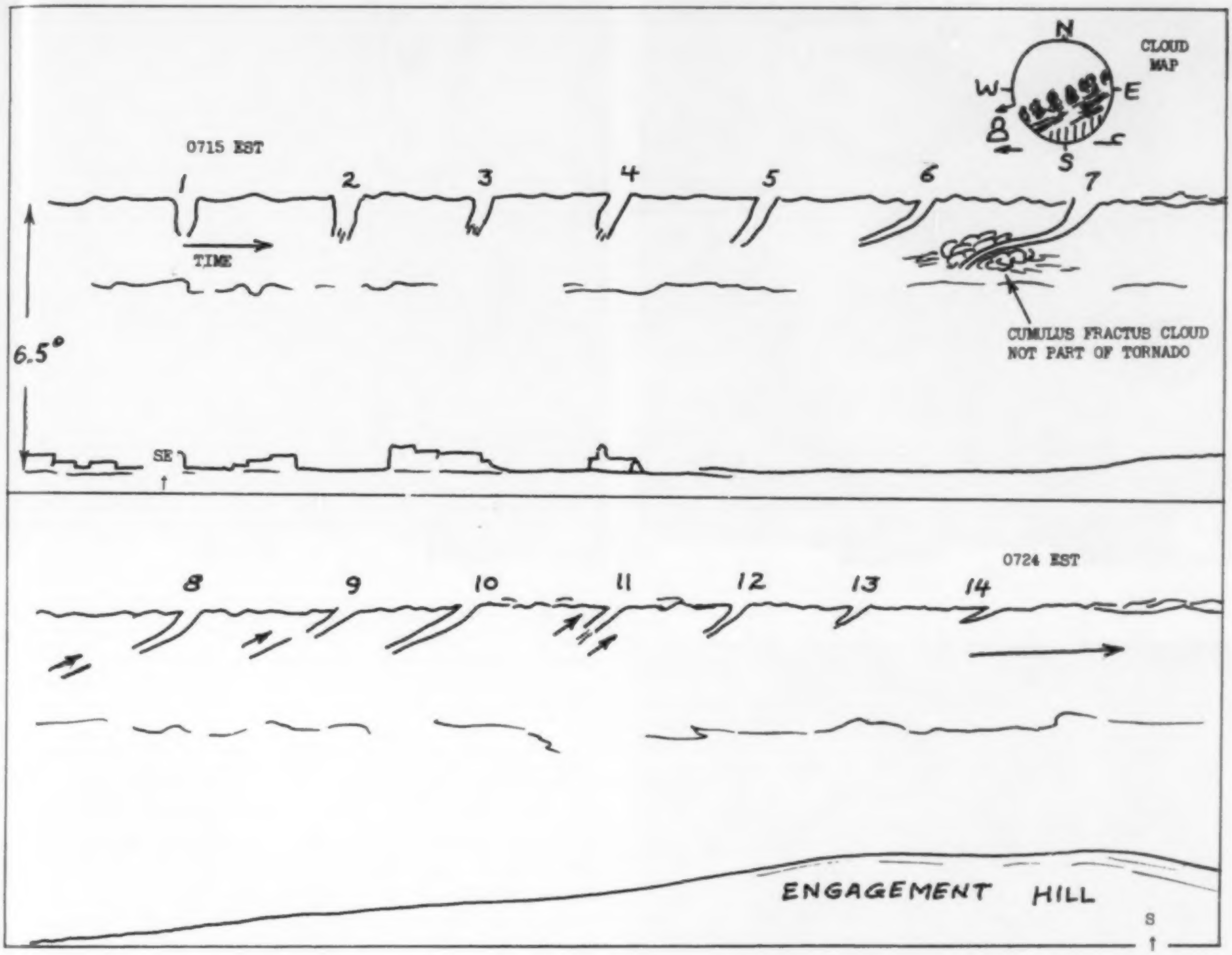

FIGURE 4.—Evolution of tornado-waterspout at Nags Head, June 27, 1960, 0715 to 0724 EST. The detached tip of stage 8 moved toward the main tube and became part of the tornado in stage 10. Along-the-tube motion was observed in stages 8, 9, and 11. The horizontal distance moved by the system was 40° of arc.

figure 1 is B and C and the second pair is E and F, while pendant D had no accompanying vortex in figure 1. Vortex D–1 appeared in figure 2 while pendants A, B, and C had probably degenerated into a single pendant beneath a flat-bottomed cloud. In figure 3, D and D–1 persisted while possibly E and G also remained. Pendant G existed throughout the series of three pictures.

2. TORNADOES ON JUNE 27, 1960

On the morning of June 27 two tornadoes were seen; the first was observed between 0715 and 0724 EST, and was unusual in that it moved from the east-northeast. It occurred in a fairly compact band of cumulus congestus which was oriented west-southwest to east-northeast. The surface wind was northeast 8–10 m.p.h. and the cumulus bases (appearing like cumulus fractus) moved from the east while the cumulus congestus tops moved from east-northeast. These cumulus congestus were not especially massive nor were their tips markedly high. There was no rain, thunder, or lightning, nor any agitation in the bases of these clouds. This incident clearly demonstrates the fact that these smaller tornadoes can and do develop in weather that is not particularly threatening and that no natural warning in the form of thunder necessarily accompanies the vortex.

Most of the lifetime of this tornado was observed through binoculars and the steps of its development are illustrated in the sketches of figure 4. When first seen it was a stubby, broad, and vertical pendant, as in sketch 1, which never reached as much as one-fourth of the way to the earth's surface. The lower end gradually inclined toward the left (trailing portion) without much lengthening until sketch 5, when the cloud tube started to lengthen, bend,

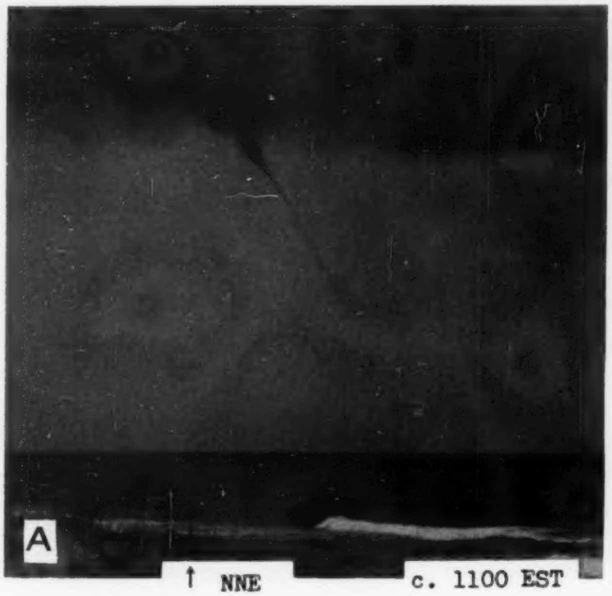

FIGURE 5.—Photographs made 3 miles from the tornado-waterspout of June 27, 1960, from 1100 to 1112 EST. Note the long stinger and slender taper in sections A and B, and the final stubby pendant in section C. Photos by Richard E. Jordan, Nags Head, N.C.

taper, and narrow. In its last two minutes it became gradually shorter and narrower, and as it finally disappeared it was almost horizontal (sketch 14). The funnel was mostly dark and opaque, but in sketch 7 it was light gray in its lower part and showed to advantage against the dark background of cumulus fractus, which latter was not part of the tornado. However, in sketch 10 it was translucent.

The few instances in which an updraft could be observed are marked by short arrows. The apparent movement of the thread-like cloud tube toward the funnel in sketches 8 and 9, which was rather rapid, may have been a growth or lengthening of the tube rather than a movement. But the fact that there was a simultaneous disappearing of the lower end of this tube, though not as fast as the extension of the upper end (resulting in a lengthening of the tube) leads me to think that there was an updraft involved in the movement of the cloud. In sketch 8 the thread-like lower cloud seemed to be along the vortex axis, but it joined the upper edge of the funnel base and immediately the funnel lengthened (sketch 10) with considerable width; it seemed as if the thread-like cloud had been just the higher edge of a fairly thick inclined vortex.

As mentioned above, there was a second tornado on this morning of June 27. It was photographed by Mr. R. E. Jordan who took his first exposure close to 1100 EST, 9½ minutes before I saw it. He was three miles from its nearest approach. His first photograph is reproduced in figure 5A, which shows a slanting funnel with a very long and narrow stinger; no spray bush is visible, but another observer who was in a direct line with the tornado's approach saw a spray bush that broke up when the bush came within a half-mile of the shore. This observer also saw a tube extending all the way from the cloud base to the sea in the early stages, and it appeared that the tornado was lifting water "right up into the sky." Mr. Jordan's second photograph, figure 5B, shows the upper funnel apparently a little longer and the thin stinger a little shorter than earlier.

By 1109:30 EST, I saw this tornado-waterspout and real-

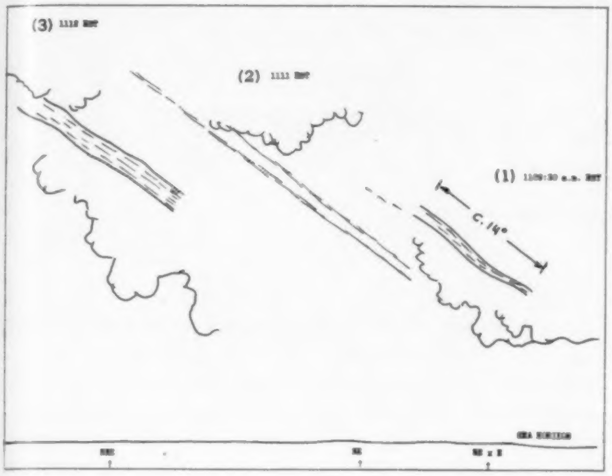

FIGURE 6.—Three stages of the second tornado-waterspout of June 27, 1960, between 1109:30 and 1112 EST, as seen by the author from ½ mile away. Rather than narrowing with time as other tornadoes have done, this tornado became thicker in its trunk portion.

ized that it was much larger than the earlier one. At this time I was about 1 mile from it and could see it in detail. Its direction was from the east in contrast to the usual tornado movement from a westerly direction. In figure 6, are three sequences sketched as I saw them, and these follow the first two pictures taken by Mr. Jordan (fig. 5).

The tornado hung from a fairly large cumulus and its tube was translucent with a double wall beautifully formed. In sketch 2 (fig. 6), at 1111 EST, the tube was very straight and its slope exactly matched the slope of the cloud base into which it extended. In sketch 3, at 1112 EST (nearly the same time as the third picture by Mr. Jordan (fig. 5C)) the tube suddenly grew wider and suddenly dissolved as it was widening. Its width appeared uniform along its length at this time, probably an effect of perspective as the lower end pointed more nearly toward me. At this stage the tube was a smooth gray color, but it grew fainter as it widened, and maintained the appearance of translucence. Instead of disappearing into a level cloud base as it seems in figure 5C, it slanted up along the side of a ragged cumulus, merging slightly with it. Much of the lower tube as I could see it does not show in the picture (fig. 5C) because of an intervening cloud.

The cumulus congestus cloud from which the tornado extended was part of a loosely assembled band or row of cumulus congestus oriented about northeast-southwest. These clouds were not very tall, but had hard edges at the top. Some of the tops had excessively large pileus over them and their color was not white but dirty-looking; they were most likely not frozen. As with the earlier tornado on this day, there was no rain, thunder, or lightning with this larger tornado-waterspout and there was no agitation in the cloud around the funnel or tube, no more than in an ordinary cumulus base. The system seemed to move quite rapidly during the 2½ minutes that I observed it. Surface temperature and dew point were 79° and 66° F., respectively, and the wind gradually changed from northeast to southeast during the morning.

Several people here have reported seeing two funnel clouds southeast of Nags Head at 0500 EST existing simultaneously. This makes a total of 4 known tornadoes or funnels in this vicinity in one morning.

I got the impression that there was an instability line with intermittent cumulus congestus activity along it, which drifted slowly northward during the morning. After the 1100 EST disturbance, the line of cumulus congestus moved to the north, and cumulus humilis became more predominant with only isolated cumulus congestus later, still moving from the east.

The writer hopes that these observations will add to the knowledge of tornadoes in general, and that they can be used by those who are searching for the yet elusive specific cause of these phenomena.

NOTE BY W. H. HOECKER—The importance of the bulbous pendants accompanying the vortices described in figures 1–3 is emphasized by the observation of a similar pendant which accompanied the earlier stage of the Dallas tornado of April 2, 1957, and which was actually larger than the tornado at one time Figure 2 shows that the pendant at Nags Head accompanying the vortex D–1 was larger than the vortex, but for the two other pairs the vortex appeared larger, at least at the time of the photographs from which the sketches were made.

The importance of the observations for June 27 involves the unusual direction of movement of these tornado-waterspouts from the east and the fact that there was no natural warning to residents in the form of lightning and thunder or associated wind. Also of importance is the shape evolution of the second tornado of June 27. Contrary to a scheme of being short and wide in the early stage and narrowing and lengthening at the late stage, as was characteristic of Great Plains tornadoes investigated by Hoecker [2,3], this tornado was long and slender when first observed and evolved into a short, stubby pendant.

Much is yet to be learned about the inception and evolution of the tornado and it is thought that these observations, by their unusual nature, will point to a generalized concept of tornado formation and life history.

ACKNOWLEDGMENT

The writer is indebted to Mr. Walter H. Hoecker, Jr., of the U.S. Weather Bureau, Washington, D.C., for his excellent suggestions, and his extensive labor in compiling and editing the figures and material in this note.

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THE WEATHER AND CIRCULATION OF OCTOBER 1960[1]

J. F. ANDREWS

Extended Forecast Section, U.S. Weather Bureau, Washington, D.C.

1. INTRODUCTION

Generally fine fall weather prevailed throughout most of the United States during October 1960. The days were pleasantly warm and the nights cool. There was very little severe storm activity, and no tropical storms were observed in the Atlantic, Caribbean, and Gulf of Mexico.

Principal exception to the good weather occurred over the Southwest where Arizona, New Mexico, and Texas reported record or near record amounts of precipitation for the month, with flash flooding a frequent occurrence in Texas.

2. MONTHLY MEAN CIRCULATION AND WEATHER

MEAN CIRCULATION

The most anomalous feature of October's average circulation pattern at 700 mb. (fig. 1) was strong blocking over the North Atlantic, where heights averaged as much as 390 ft. above normal. During September [1] blocking had been centered just north of Scandinavia. As the blocking moved westward, it increased in strength and was associated with development near Ireland of a deep mean Low both at 700 mb. and sea level (figs. 1 and 2). The presence of a cyclonic center on a monthly mean map in this area is most unusual, none previously having been observed during our period of record (since 1932). Average sea level pressures in this Low were as much as 12 mb. below normal (not shown), while heights at 700 mb. were 400 ft. below normal.

Retrogression and intensification of the block was also associated with development of a deep full-latitude trough over central Asia (fig. 1). Perhaps as a result, the mean troughs near the Asiatic coast, over the mid-Pacific, and off the California coast moved eastward from September to October. The full-latitude trough near the east coast of North America during September deepened at middle latitudes as its lower portion moved slowly eastward in October. At higher latitudes, however, this trough weakened and retrograded as blocking from the North Atlantic spread into eastern Canada, the trough assuming more of a negative tilt.

Wind speeds at 700 mb. also reflected the blocking character of the circulation over the Atlantic. Note in figure 3A the characteristic split jet stream over the Atlantic and Europe, with wind speeds up to 7 m.p.s. above normal at high latitudes and as much as 9 m.p.s. above normal at lower latitudes (fig. 3B). An extensive area of subnormal wind speeds, as much as 7 m.p.s., was observed at middle latitudes. The axis of maximum west winds across the Atlantic was displaced south of normal (normal position is shown by dashed line) as a result of the blocking. Elsewhere around the hemisphere, the jet axis appeared as a well defined current, north of its normal position over eastern Asia and the western Pacific, and near its normal position over the eastern Pacific and across North America (fig. 3A). Wind speeds in the latter two areas were close to their normal values (fig. 3B). This is also implied by small departures from normal of 700-mb. heights (fig. 1).

AVERAGE UNITED STATES WEATHER

October was generally warm over most of the contiguous United States, with below normal temperatures observed only in the Plateau States, the Northeast, and in portions of the Upper Mississippi Valley (fig. 4). Temperature departures were rather small, 2° F. or less over most of the Nation, although positive departures of as much as 4° F. were observed in southeastern Montana (fig. 4).

The predominantly mild weather can be related to the weaker than normal ridge over western Canada (fig. 1). As a result of the weakness of this ridge, relatively mild Pacific air masses dominated the Nation's weather. Over the Great Basin, however, strong radiational cooling in the mean sea level High (fig. 2) resulted in below normal temperatures. The cool conditions in Arizona and New Mexico can be related primarily to southward advection of Pacific air masses into a stronger than normal trough aloft (fig. 1), and also to cloudiness and precipitation from a very slow moving storm near mid-month. In the Northeast below normal 700-mb. heights and northerly, anomalous flow resulted in cool conditions (figs. 1 and 4). From the Middle Atlantic States to the Gulf of Mexico this flow diminished in strength, and, combined with a weak confluence zone over the middle United States, tended to prevent the southward intrusion of cooler conditions.

[1] Articles on the weather and circulation of November 1960, December 1960, and January 1961 will appear in the February, March, and April 1961 issues, respectively, of the *Monthly Weather Review*.

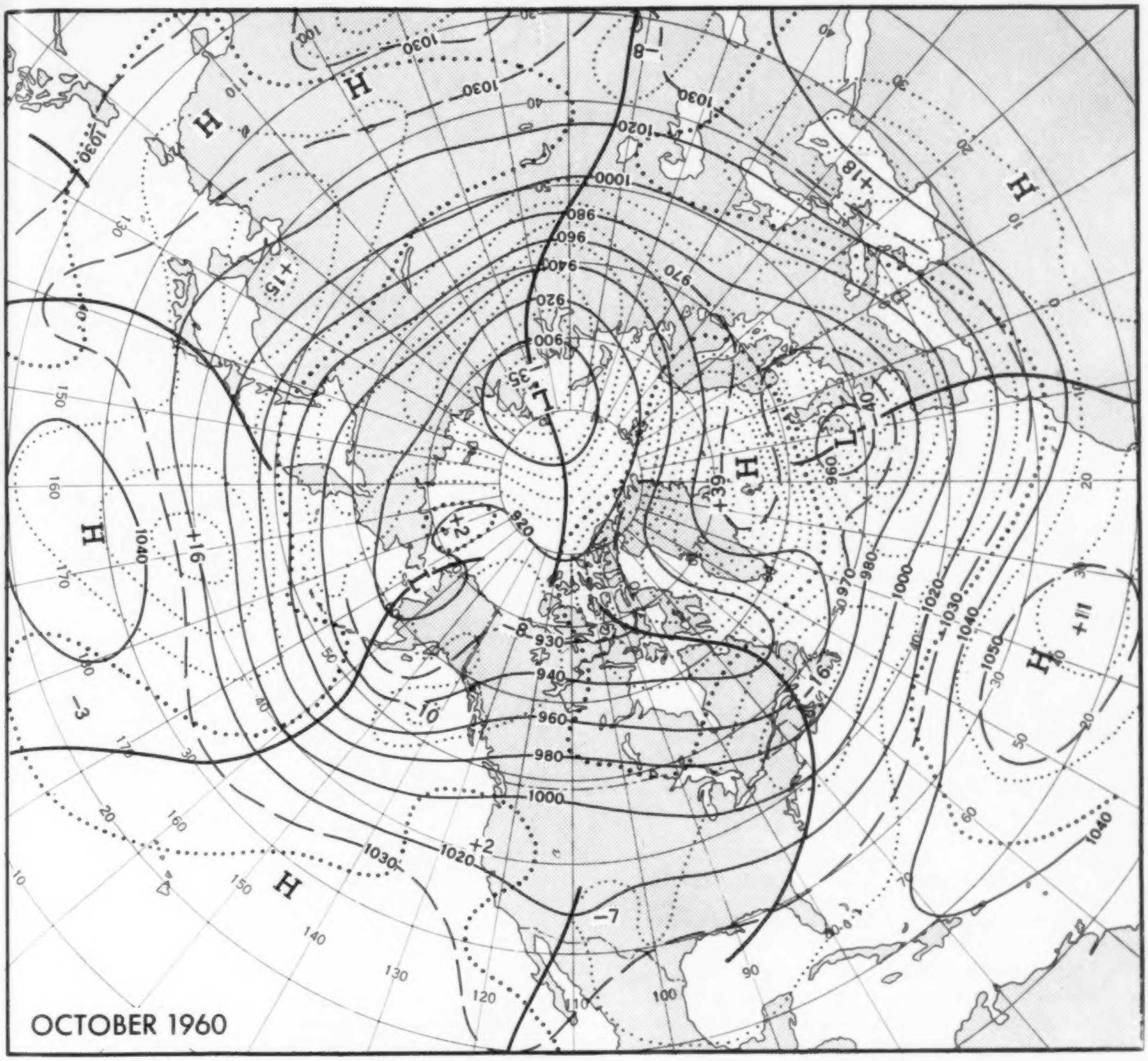

FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for October 1960. Blocking pattern in the Atlantic was the outstanding circulation feature of the month.

The outstanding feature of the precipitation pattern for October was the large area in the Southwest where amounts were far in excess of the monthly normal (fig. 5). As much as six times the normal amount of precipitation fell in portions of southeastern Texas. Victoria reported 17.25 inches, an all-time record for any month, while Corpus Christi, with 10.66 inches at the airport and 15.49 inches at the Weather Bureau city office, had its rainiest October in a period of record dating back to 1887. At Austin, Tex., rainfall of 12.31 inches was the second heaviest on record for October. The heavy precipitation in the Southwest was related to the deeper than normal trough in that area (fig. 1) and to cyclonically curved southeasterly flow of Gulf moisture at the surface (fig. 2). This weather pattern replaced the upper level anticyclone and generally dry conditions which had prevailed during September [1].

Near normal amounts of precipitation fell over much of the East. This was related primarily to cyclonic curvature of the contours and below normal 700-mb. heights in the mean trough along the east coast.

Less than half the normal amount of precipitation fell

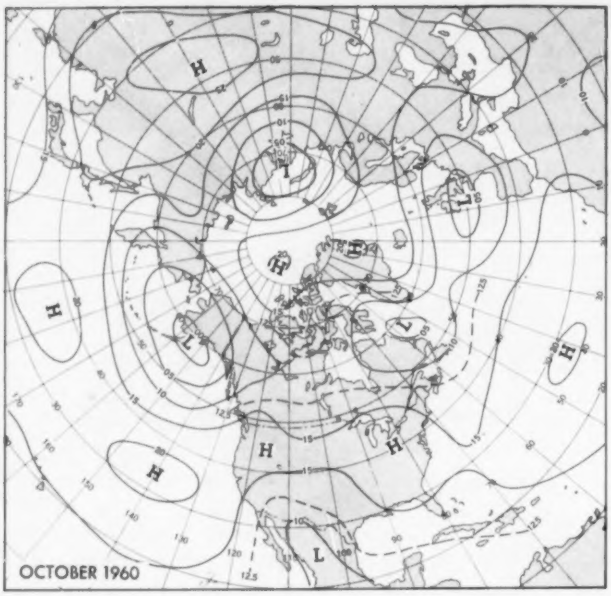

FIGURE 2.—Mean sea level isobars (millibars, hundreds omitted) for October 1960. Low cells and storm track in the North Atlantic were displaced well south of normal.

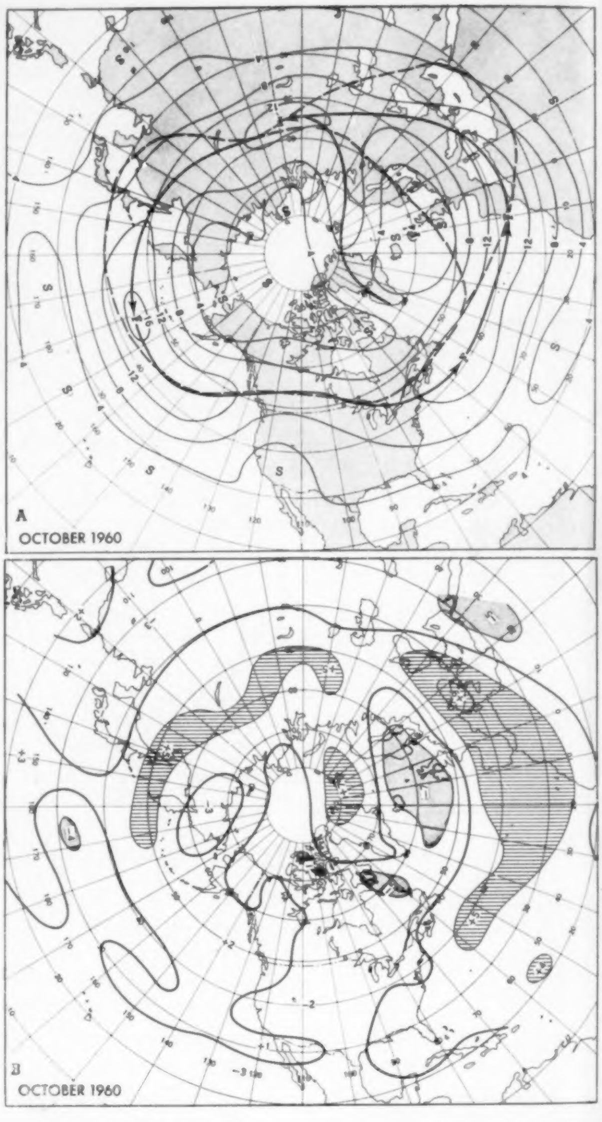

FIGURE 3.—(A) Mean 700-mb. isotachs and (B) departure from monthly normal wind speed (both in meters per second) for October 1960. Solid arrows in (A) indicate axes of primary wind speed maxima with the normal position dashed. Areas of departures in (B) greater than +4 are hatched, those greater than −4 are stippled.

in the Great Basin, most of California, and the northern Great Plains (fig. 5). No measurable precipitation fell at Rapid City, S. Dak. during October; none had fallen since September 22. Anticyclonic curvature and a weak ridge aloft (fig. 1) contributed most to this precipitation deficiency.

SOME CHARACTERISTICS OF EUROPEAN WEATHER

In this section special attention will be devoted to October's weather in Europe because of the unusual nature of the monthly mean circulation observed in that area. The average weather observed in Europe during October can be divided roughly into three regimes: cool and dry in the north, cool and wet in the south, and warm and wet in the middle countries. In figure 6A is shown the average surface temperature and its departure from normal for selected European cities during October 1960, while figure 6B gives the total precipitation and percentage of normal for the same cities. These data are from [2]. Normals used are based on a 30-year average (1901–30 when available) as recommended by the World Meteorological Organization.

Unusually heavy amounts of precipitation fell in most areas, with only the northern portions of the British Isles and Scandinavia receiving substantially less than normal amounts. Many countries received more than twice their normal rainfall for the month, while much of Spain had more than three times the normal. In general, the greatest falls and percentages were found in areas closest to the Atlantic Ocean. La Coruna, Spain received 10.63 inches, and Brest and Bordeaux, France 8.66 inches each. In many areas this was the wettest October in several decades, and flooding was reported throughout much of western Europe.

The unusually wet weather was well related to October's mean circulation pattern. Of most importance was the deep mean trough along the coast of western Europe and the intense cyclonic center of action near Ireland (figs. 1 and 2). Abnormally strong Atlantic westerlies, aided by orographic lifting, dropped much of their moisture near and

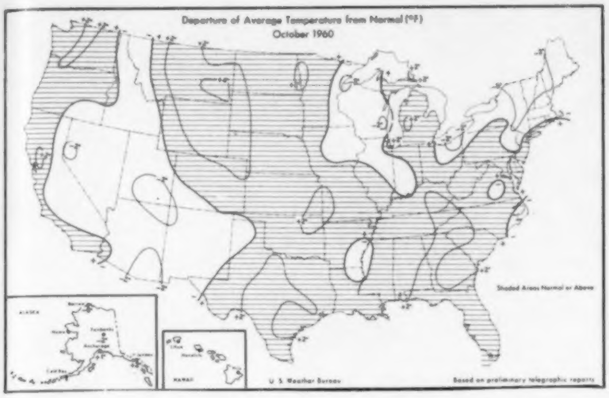

FIGURE 4.—Departure of average surface temperature from normal (° F.) for October 1960. Departures were generally small for the month. (From [6].)

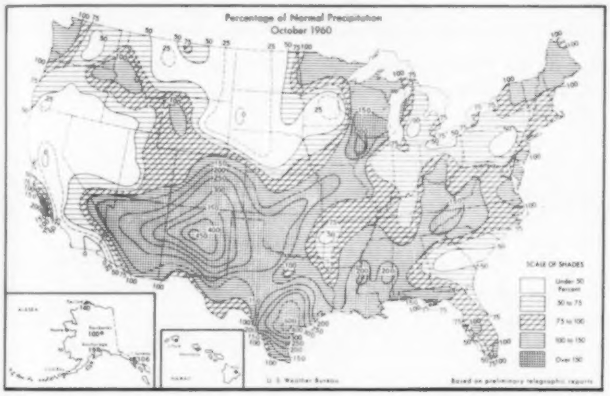

FIGURE 5.—Percentage of normal precipitation for October 1960. Far more than normal amounts fell in the Southwest. (From [6].)

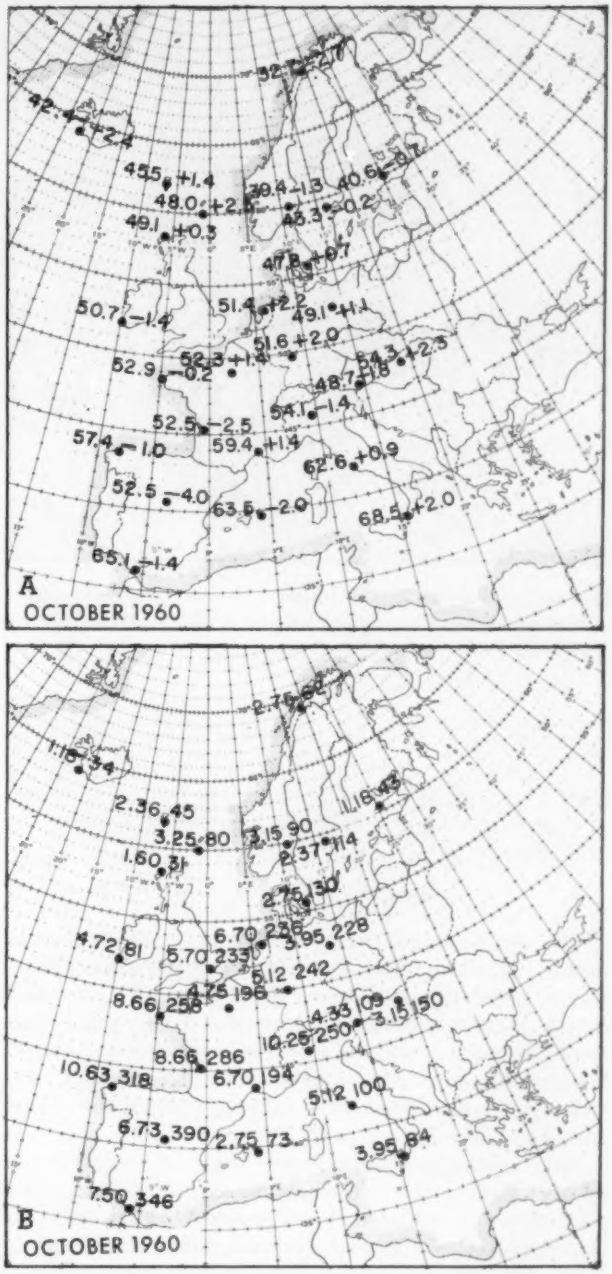

FIGURE 6.—(A) Average surface temperature and departure from normal (° F.), and (B) total precipitation (inches, approximate) and percentage of normal for October 1960 at selected European stations.

along coastal areas, with somewhat lesser precipitation amounts farther inland. Much of the band of heaviest precipitation fell near or to the north of the primary jet axis at 700 mb. (fig. 3). At sea level, storms moving across the Atlantic reached their maximum intensity near the coast before moving inland and weakening. The path of these systems was well defined by the zonal trough on the mean sea level chart (fig. 2).

The strong upper level ridge near Greenland and the accompanying lack of cyclonic activity were related to above normal temperatures and a precipitation deficiency in Iceland, while stronger than normal northerly flow resulted in below normal temperatures and subnormal amounts of precipitation throughout most of Scandinavia (figs. 1, 2, 6). A strong onshore flow of relatively cool Atlantic air, combined with persistent cloudiness and precipitation, produced cooler than normal conditions in southwestern Europe, where Madrid, Spain, reported a temperature departure of −4°F. In central and southeastern Europe prevailing southerly flow at sea level and aloft resulted in generally warmer than normal conditions.

3. WEEK-TO-WEEK VARIABILITY

Rather marked week-to-week changes occurred in the circulation and weather over the contiguous United States during October. These changes will be described

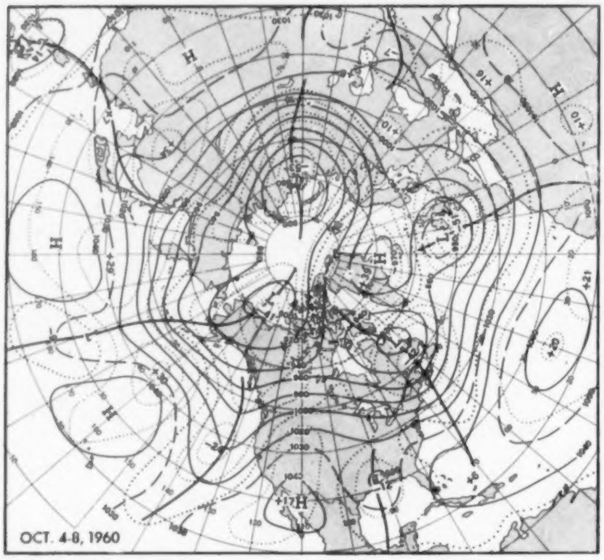

FIGURE 7.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for October 4–8, 1960.

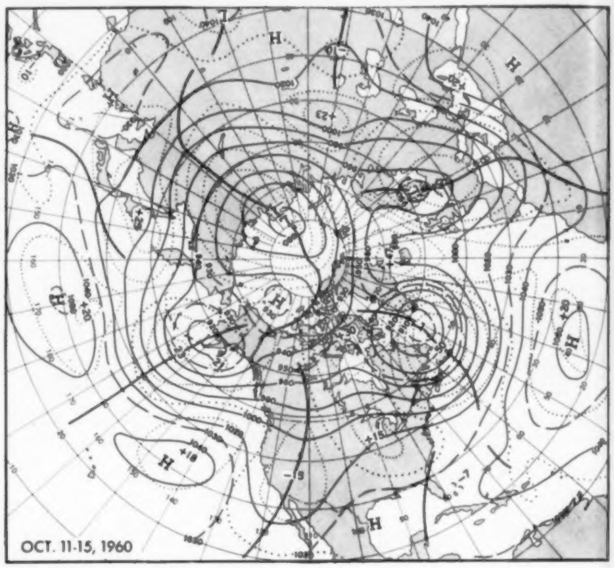

FIGURE 8.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for October 11–15, 1960.

using a series of 5-day mean 700-mb. charts centered one week apart. The reader is referred to the corresponding maps of weekly temperature departure from normal and total precipitation published in the *Weekly Weather and Crop Bulletin* [3].

WEEK ENDING OCTOBER 9

The month began with the westerlies stronger than normal, troughs off both east and west coasts of the United States, and a strong ridge over the West (fig. 7). Another trough, seemingly out of place because of high zonal index conditions and short wavelength, was found over the Gulf of Mexico. The circulation in the Atlantic was strikingly similar to the mean pattern for the month (compare figs. 1 and 7).

Mild Pacific air masses dominated the United States and resulted in above normal temperatures over all but the extreme northwestern and northeastern sections of the country [3]. Greatest weekly departures, as much as 9° F. above normal, were observed in the northern Great Plains. A temperature of 91° F. at Bismarck, N. Dak. on the 4th equalled their previous record high for so late in the season. This unseasonable warmth was related to the strong upper level ridge over the West, and to the extensive area of negative 700-mb. height anomaly over western Canada (fig. 7). It has long been known that negative height anomalies over western Canada during the cooler seasons are associated with above normal temperatures over most of the United States, with the converse also true. Cool weather in the Northeast was related to stronger than normal northerly circulation around the deep center of action over eastern Canada (fig. 7).

Little if any precipitation fell in the area from the Rockies to the Great Lakes, under the influence of dry, northwesterly flow aloft (fig. 7). The heaviest and most frequent precipitation fell over the southeastern quarter of the Nation, with amounts of 2 inches or more quite general. These heavy rains were related to a slow moving trough and cyclonic center over Louisiana and Mississippi. Precipitation in the Far West was associated with the approach of the deep trough off the coast. As this trough moved eastward, a storm developed over the Far Southwest late in the week, bringing heavy precipitation to that area.

WEEK ENDING OCTOBER 16

Eastward motion of all trough-ridge systems occurred from the first to the second weeks under the influence of continuing fast westerlies. The trough over the Gulf of Mexico and Gulf States filled considerably as it moved eastward (fig. 8). As a result little if any rain fell in the Southeast.

Eastward motion was also observed in the temperature patterns between the two weeks. Cold Pacific air masses accompanied the eastern Pacific trough into the Far West, where temperatures for the week averaged as much as 9° F. below normal in southern Nevada and southeastern Idaho.

Abnormally warm weather overspread the East to include all but northern New England, where a persistent northerly circulation kept temperatures below normal (fig. 8). Escanaba, Mich., reported its highest tempera-

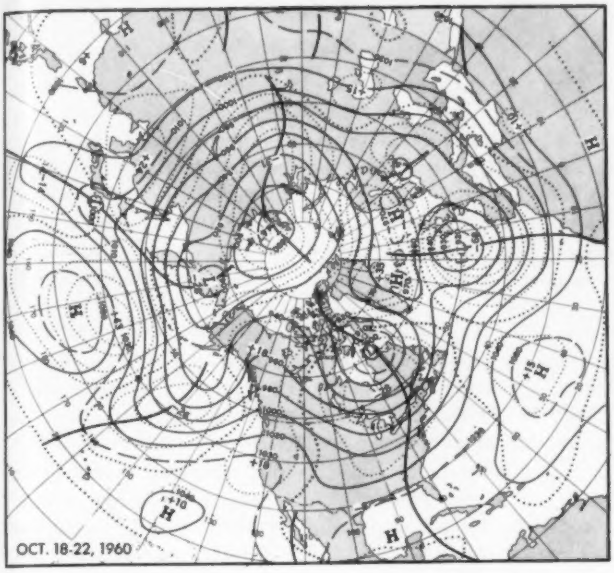

FIGURE 9.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for October 18–22, 1960.

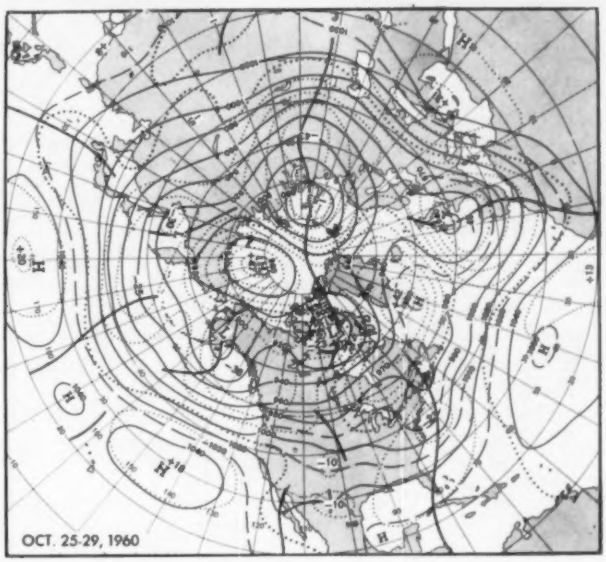

FIGURE 10.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for October 25–29, 1960.

ture so late in the season, 82° F. on the 10th. Daily temperature records were established at Des Moines, Iowa (86°) and Topeka, Kans. (87°) on the 11th, Detroit, Mich. (81°) on the 13th, and Providence, R.I. (81°) on the 15th.

The deep trough in the West spread heavy rains from the lower Great Plains to the Great Lakes, with greatest amounts in Texas. As much as 12 inches fell in the southern part of that State. Precipitation at Denver, Colo., on the 13th ended a 20-day period without measurable precipitation and the driest August 1–October 12 period of record. The rainfall occurred as a storm system developed over the Far Southwest and became trapped by a massive high pressure area to the north. As a result, precipitation persisted in the southern Rocky Mountain States for four to five days, carrying over into the following week. Roswell, N. Mex., reported a near record 24-hour amount on the 16th–17th. The cutting off and stagnation of this storm was related to amplification of the circulation in the eastern Pacific near the end of the week.

Western Europe had its most favorable weather of the month during the second week as the trough near the coast moved eastward into central Europe (fig. 8).

WEEK ENDING OCTOBER 23

A complete reversal of circulation and temperature regimes occurred between the second and third weeks in the United States. This change was effected primarily by amplification and eastward motion of the trough-ridge system in the eastern Pacific. As a result a strong full-latitude ridge developed over the coast of western North America, with positive height anomalies replacing the negative field of the previous week (figs. 8, 9). At the same time the trough over the West moved eastward to the Appalachians, where ridge conditions had prevailed the week before. Marked changes also occurred downstream, with the circulation reverting to the same general pattern as observed during the first week (figs. 7, 9).

Stronger than normal northwesterly flow over western North America (fig. 9) deployed cold, continental polar air masses into the eastern two-thirds of the United States, thus bringing to an abrupt end the warm regime of the week before. Early season minimum temperature records were established on the 19th at Bismarck, N. Dak. (5°) and Huron, S. Dak. (11°), and on the 20th at Sioux City, Iowa (16°) and Topeka, Kans. (22°). The circulation reversal in the West was also accompanied by a reversal in temperature regimes, with some areas averaging 10° F. warmer than the previous week.

Continuation of trough conditions in the Southwest brought additional heavy rains to the Southern Plains, with Texas again receiving the heaviest amounts. Up to 10 inches fell in the middle Texas coastal region, resulting in considerable flash flooding. Eastward motion of the trough in the West also brought substantial amounts of precipitation to the Atlantic Coastal States.

WEEK ENDING OCTOBER 30

Intensification and retrogression of North Atlantic blocking dominated the circulation changes toward the end of the month. Heights at 700 mb. rose as much as 500 feet over southeastern Canada, while an increase of 700 feet was observed north of the Siberian Peninsula

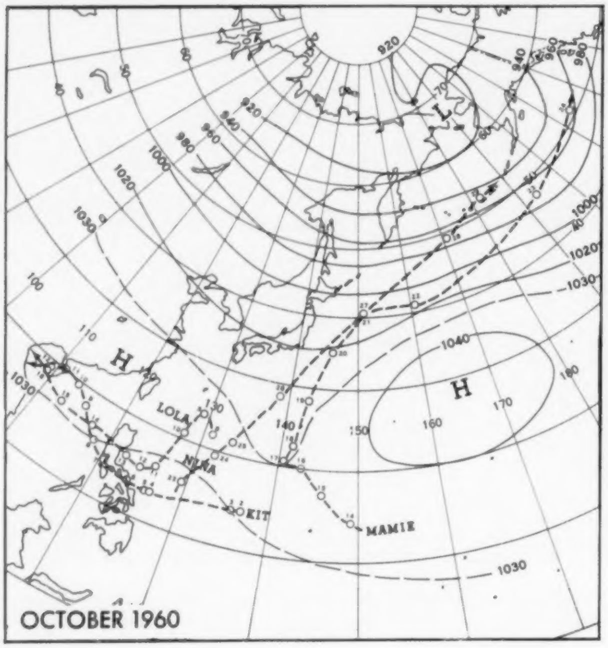

FIGURE 11.—Tracks of Pacific typhoons superimposed upon mean 700-mb. height contours (same as fig. 1) for October 1960. Open circles and dates indicate 1200 GMT positions.

(figs. 9, 10). As a result, the middle-latitude westerlies diminished in strength, with the circulation pattern characterized by a series of truncated trough-ridge systems with relatively short wavelengths.

Collapse of the ridge over western North America resulted in milder Pacific air and above normal temperatures spreading eastward to the Mississippi Valley. Most of the East continued cool because of stronger than normal northerly circulation (fig. 10).

For the third consecutive week heavy rains fell in central and southeastern Texas, causing major flooding along several streams. Amounts of 5 to 10 inches fell south of San Antonio on the 25th and from 7 to 10 inches in the Austin area on the 28th. Heavy amounts also spread northward into the western Great Lakes region. Much of this precipitation can be related to a developing lee trough east of the Rockies and to maintenance of the southwestern trough.

Several slow moving storm systems, deepening in the trough off the east coast, brought heavy precipitation to the Middle Atlantic coast and the Northeast. Some of this was in the form of an early season snowfall in Pennsylvania, New York, and New England. Amounts were generally light, but up to 6 inches was reported in New Hampshire.

4. TROPICAL ACTIVITY

ATLANTIC

There was a complete lack of tropical storm development in the Atlantic during October 1960. This compares with an average frequency of two such storms for October for the period 1887–1956. This absence of tropical activity was quite well related to the anomalous character of the circulation over the Atlantic, i.e., westerlies and subtropical ridge south of normal (figs. 1, 3), and is in agreement with the findings of Ballenzweig [4].

PACIFIC

Four typhoons were observed in the Pacific during October 1960. Tracks of these storms superimposed upon the 700-mb. monthly mean circulation (same as fig. 1) are shown in figure 11. It may be recalled that during September 1960 [1] four tropical storms were observed in the western Pacific, none reaching typhoon intensity. However, during October all storms were of typhoon strength. Normally tropical activity in the western Pacific decreases from September to October [5]. The relative increase between these two months during 1960 was probably related in part to the northward displacement of the mid-tropospheric westerlies and subtropical ridge (fig. 1). As a result the axis of maximum west wind at 700 mb. was some 10° north of normal over eastern Asia and the western Pacific (fig. 3A).

Typhoons Kit and Lola developed during the first half of the month. Both followed similar westward courses, south of the subtropical ridge axis, as they passed through the Philippines into the South China Sea before dissipating over land. Note how closely their paths followed the 10,300-ft. contour (dashed) of the monthly mean 700-mb. chart (fig. 11). Typhoons Mamie and Nina, on the other hand, developed during the latter half of the month and recurved northward into the westerlies. Here they became severe extratropical systems as they moved rapidly eastward, Mamie reaching a minimum sea level pressure of 952 mb. in the Gulf of Alaska on the 24th, while Nina deepened to 968 mb. on the 29th and 30th.

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